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TOPICAL REPORT

REGENERATIVE FUEL CELL ENERGY STORAGE SYSTEM FOR A LOW EARTH ORBIT SPACE STATION

By

R. E. Martin
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United Technologies Corporation
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Prepared for

National Aeronautics and Space Administration

Contract No. NAS3-22234
Task No. IX

NASA-Lewis Research Center
Cleveland, Ohio

Mr. Dean W. Sheibley, Project Manager

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NOTICE

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FOREWORD

This topical report presents results of a study to define the characteristics of a Regenerative Fuel Cell Energy Storage System for a large space station operating in low earth orbit (LEO). The Regenerative Fuel Cell System employs an alkaline electrolyte fuel cell with the option of employing either an alkaline or a solid polymer electrolyte electrolyzer.

The study was conducted for the National Aeronautics and Space Administration-Lewis Research Center under Contract No. NAS3-22234, Task IX, Regenerative Fuel Cell System (RFCS) study and Engineering Model System (EMS) Space Prototype Design from 1 October 1983 through 30 July 1984.

The NASA Project Manager for this contract was Mr. Dean W. Sheibley. The contributions of Mr. Sheibley and other members of the Electrochemistry Branch staff at NASA-LeRC are gratefully acknowledged.

The Project Manager for Power Systems Division (PSD) was Mr. R. E. Martin with system engineering provided by Mr. J. Garow and Mr. K. B. Michaels. Computer programming assistance at PSD was provided by Mr. L. S. Rec.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

I. SUMMARY

Scope of Study

This topical report presents the results of a study performed under Task IX of NASA Contract NAS3-22234. The study defined the characteristics of a Regenerative Fuel Cell System (RFCS) system for Space Station applications. These results may be used directly in Phase B Space Station studies. The RFC may be a stand-alone energy storage system, can be integrated with other station systems such as environmental control and propulsion and can supply emergency or peak load power. This operating flexibility can provide important benefits in initial Space Station construction and other phases of normal and emergency operation. The value of these benefits must be determined in the Phase B studies.

The pacing technology items for achieving a 1991 initial operational capability (IOC) were identified and development plans for each were established. A 10-kW Engineering Model System (EMS) demonstrator unit was defined and characterized. An EMS development program plan was prepared.

RFC Baseline System

The baseline system is composed of several RFCS modules, each consisting of a fuel cell integrated with an electrolyzer unit, as shown in Figure 1. The fuel cell and electrolyzer are mounted in a common support structure with accessories and controls, as shown in Figure 2. This arrangement is one of several that are possible. Reactant storage can be located remotely or in close proximity to the RFCS module.

In addition to operation in the cyclic energy storage-energy supply mode, the RFCS is capable of continuous operation as either a fuel cell or an electrolysis unit, using externally supplied reactants or water, respectively. This permits integration of the RFCS with other station systems, and also allows the RFCS to provide emergency power and power during station construction. The baseline RFCS can be based on either the alkaline or acid solid polymer electrolyte (SPE) electrolyzer.

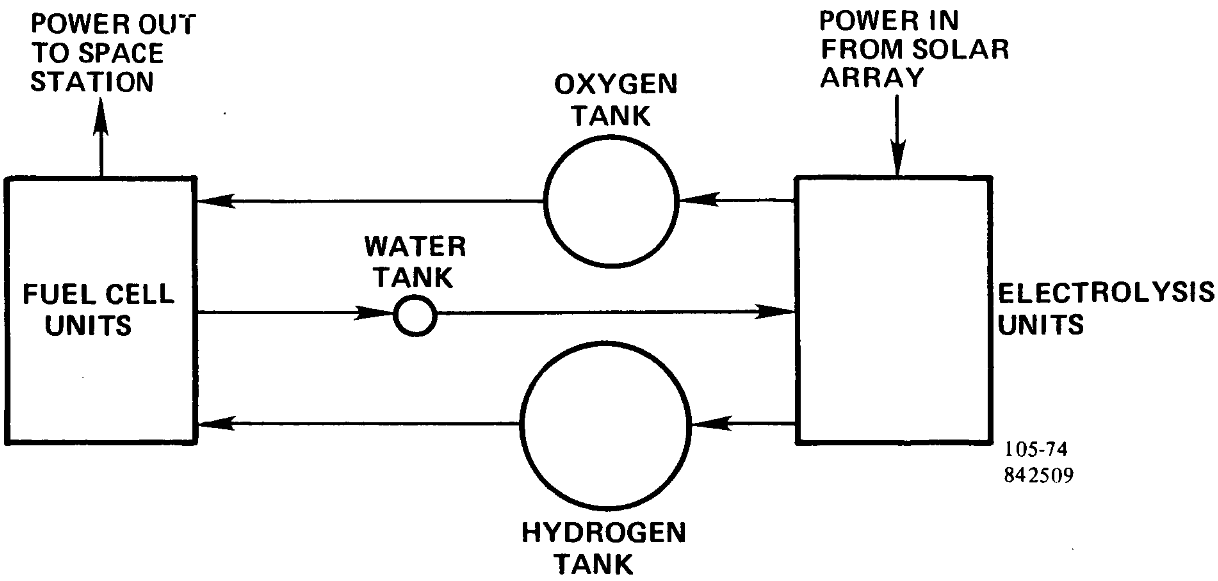

Figure 1. Baseline Regenerative Fuel Cell System

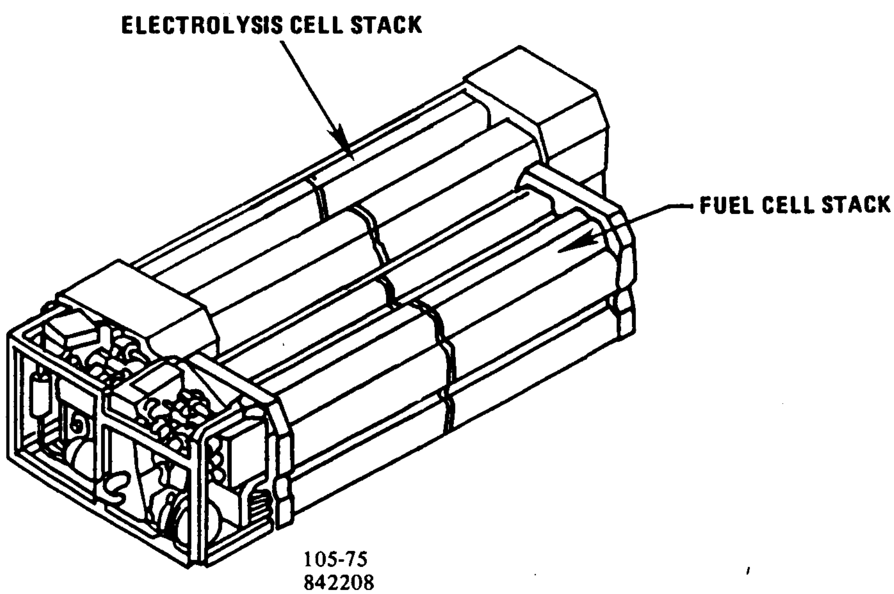

Figure 2. Baseline Regenerative Fuel Cell Module

Both electrolyzers have similar physical and performance characteristics but result in varying system complexities when combined with an alkaline fuel cell. Selection of an electrolyzer type was not made in this study.

System Characteristics

The RFCS characteristics were defined parametrically for use in the Phase B Space Station trade studies. The characteristics are based on the alkaline electrolyzer. This choice results in a conservative weight estimate. The SPE electrolysis unit could provide about a 10 percent weight saving in a RFCS module.

The RFCS characteristics were determined for module power ratings of 10 kW to 50 kW, as a function of efficiency. For example, for a 100 kW station, with 33-kW modules, the RFCS specific weight and volume are 19.9 - 23.2 watt-hours/pound and 278-283 watt-hours/cubic foot, respectively, at an overall charge-discharge efficiency of 50%. The corresponding values for a 55% efficiency are 15.9-19.3 watt-hours/pound and 258-270 watt-hours/cubic foot. The lower values are based on today's Space Shuttle Orbiter power plant technology at an operating temperature of 140°F (60°C). The higher values represent a higher temperature (180°F) (82.2°C) demonstrated performance level. The development activity to demonstrate the higher temperature fuel cell materials capable of the required endurance is presently underway, sponsored by NASA, the U.S. Navy, and United Technologies.

The MTBF for the baseline RFCS system module has been estimated at 14,400 hours, with a module wearout life of 40,000 hours. The Space Station resupply period and the reliability level desired determine the number of spare on-board modules required. Several approaches to maintenance were considered in the study. Complete module changeout with Earth-based repair appears best at this time, but further study during Phase B is required.

Additional Uses of the RFCS

A unique feature of the RFCS is its capability to be integrated with other Space Station systems and its capability for use as a stand-alone power generator with an external reactant supply. The RFCS can supply (or accept) oxygen and potable water to (or from) the environmental control system; it can also supply (or accept) hydrogen and oxygen to (or from) the propulsion system. The RFCS can operate continuously on externally-supplied reactants, and thereby provide power during station construction and for emergency purposes. Taking advantage of these benefits does not significantly affect the RFCS specific weight and volume characteristics. The value that these features provide to the Space Station should be assessed in the Phase B studies.

Pacing Technology Items

Four pacing technology items for the RFCS have been identified. These are fuel cell endurance, electrolysis cell scale-up and endurance, hydrogen circulation pump bearing life, and cyclic water pump bearing and seal life. All other RFCS components are derived from existing Orbiter fuel cell hardware or are electrolysis components, with no significant technology improvement required.

Testing is presently being conducted under this contract to assess fuel cell life capability. The existing baseline cell has demonstrated 18,000 hours endurance at baseline performance levels. Improvements already identified in NASA-LeRC technology programs are projected to meet the Space Station endurance requirements. At the time of this report, two separate stacks, one of 4 cells and the other of 6 cells, have accumulated 3000 hours and 18,000 hours, respectively. Each stack is built of full-area 0.5 ft^2 cells.

A larger area (0.5 to 1-ft^2) alkaline electrolyzer cell has yet to be demonstrated in a full-scale multi-cell stack of more than six cells. Full-scale SPE electrolyzers have been fabricated, but system simplification and aerospace component development is desired.

The Orbiter hydrogen pump has demonstrated 12,000 hours of continuous endurance in a NASA-LeRC test program. When the test was terminated for bearing examination, the bearing manufacturer's evaluation showed that significant bearing life remained. The manufacturer recommended a change to fully sealed bearings (Orbiter bearings are shielded only) to ensure meeting the RFCS life goal. Testing of sealed bearings in an Orbiter hydrogen pump is now underway. At present, two pumps are being tested. One has accumulated 4000 hours and the other 500 hours. The tests are continuing.

The RFCS requires a water pump which operates cyclically. Preliminary discussions with pump manufacturers have indicated that the RFCS requirements are not particularly severe and that no significant technology challenge is envisioned. United, however, recommends long-term evaluation of candidate pumps to ensure that there are no seal or bearing problems.

EMS Demonstrator Unit

A key element in the RFCS program is the early demonstration of a RFCS module designated the Engineering Model System (EMS). The EMS will demonstrate the operational capability of the RFCS. A 10-kW unit is planned. This rating has been selected to make use of existing Orbiter components wherever possible. The demonstrator will be integrated and packaged with an electrolysis unit as an RFCS module, as shown by the example in Figure 3. It will demonstrate the integrated system and operating characteristics expected of the RFCS module.

The EMS schematic and design table have been prepared and operating characteristics defined. The EMS will provide a minimum output voltage of 100 Vdc while operating at a current density of 200 ASF, over a 58.8/35.7 minute charge discharge cycle at 270 N.M. This operating point will demonstrate an overall RFCS efficiency of 55%.

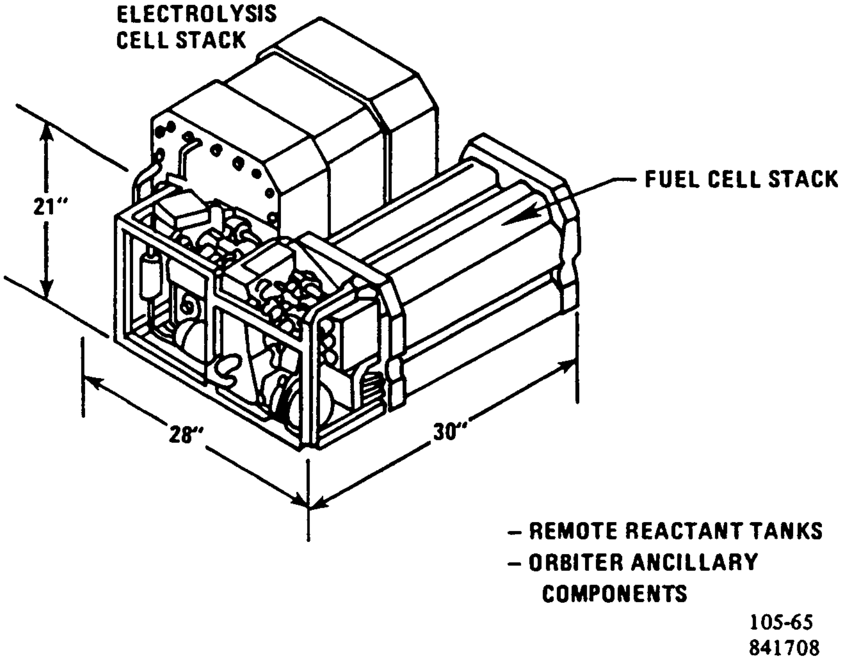

Figure 3. 10-kW Engineering Model System (EMS)

EMS Development Plan

The EMS requirements have been identified and an EMS development program planned. The key tasks in the program are system analysis, component development, and EMS design, fabrication and test. In the System Analysis Task, the EMS system will be defined, detailed component requirements will be determined, and control schedules will be established. Development test results will be analyzed and factored into systems analysis. The Component Development Task will bring the fuel cell stack, electrolyzer stack and ancillary components to a state of readiness for integration into the EMS. In the third task, a detailed EMS design will be prepared, hardware will be fabricated and the EMS will be assembled and tested.

II. INTRODUCTION

Several NASA and NASA-sponsored studies of energy storage systems for Space Station applications have shown that regenerative fuel cell systems offer significant benefit over current state-of-the-art nickel-cadmium batteries. To further examine the RFCS, Tasks IX-A and IX-B of NASA Contract NAS3-22234 were established.

In Task IX-A, known as the "RFCS Study", various system schemes for the fuel cell subsystem, gas storage subsystem, and accessories and components were studied. Emphasis was placed on water and thermal management. The objective of Task IX-B, known as the "EMS Space Prototype Design Definition", was to determine the general system requirements for an EMS prototype, define EMS parameters, and identify pacing technology items and a development program for the EMS.

The approach to the Task IX-A objective was to examine in detail several system concepts, evaluating each for weight, volume, complexity, flexibility, reliability, maintainability, development risk, etc. In addition several water management and reactant storage concepts were evaluated. The results of this study task were presented to NASA in a 26 January 1984 briefing.

In the Task IX-B phase, the baseline RFCS was further refined; subsystems were more fully integrated and several components were eliminated. The characteristics of the system were defined objectively and parametrically, to allow Phase B optimization of the RFCS. Pacing technology items were identified, and a development program plan was prepared for a 10 kW Engineering Model System (EMS) prototype demonstrator unit, which was defined and characterized. A summary of the results of this study phase was presented to NASA in a 24 July 1984 briefing.

This report is divided into seven sections. Section III describes the baseline RFCS system concept and operation. The system integrates fuel cell and electrolyzer units, which consume or produce hydrogen and oxygen in the dark and light portions of the Space Station orbit. The storage system for the reactants produced in the electrolysis mode and the water produced in the fuel cell mode, is discussed, as well as thermal management aspects.

In Section IV the characteristics of the RFCS are presented. The groundrules and assumptions used in the analyses are stated. Parametric data for specific weight, specific volume, and reactant storage systems are presented. The RFCS reliability estimates and supporting parametric data are also presented. A maintenance concept for the RFCS is discussed.

Section V identifies the pacing technology items for the RFCS and the development approach to these items. The ongoing development activity in these areas is summarized. The conclusion of this section is that no major technology hurdle stands in the way of RFCS development.

The EMS demonstrator is defined and characterized in Section VI. A system schematic, pictorial representation, and design table are presented. A description of the component technology planned for EMS incorporation is provided. The operating characteristics and control logic are described.

Finally, Section VII presents the development program for the EMS. The major segments of the program are defined and discussed, as well as the development philosophy and schedule. This plan culminates with delivery of the EMS for NASA testing.

III. REGENERATIVE FUEL CELL ENERGY STORAGE SYSTEM

This section contains the description of a regenerative fuel cell energy storage system for the Space Station based on the coupling of a hydrogen-oxygen fuel cell with a water electrolyzer and defines the basic modes of operation of such a system in low earth orbit. Also included is a detailed description of the particular baseline system arrangement chosen for study which incorporates the potential for use of either one of two types of electrolyzers.

A. System Concept

The regenerative fuel cell energy storage concept shown in Figure 4 incorporates a dedicated alkaline fuel cell module and an electrolysis cell module. The figure also shows the integration of the system with the spacecraft electrical and thermal control systems. A single power conditioner on the electrical bus for the solar array and electrolysis cell system may be possible. A modularized energy storage system is envisioned for application in a future low earth orbit space vehicle.

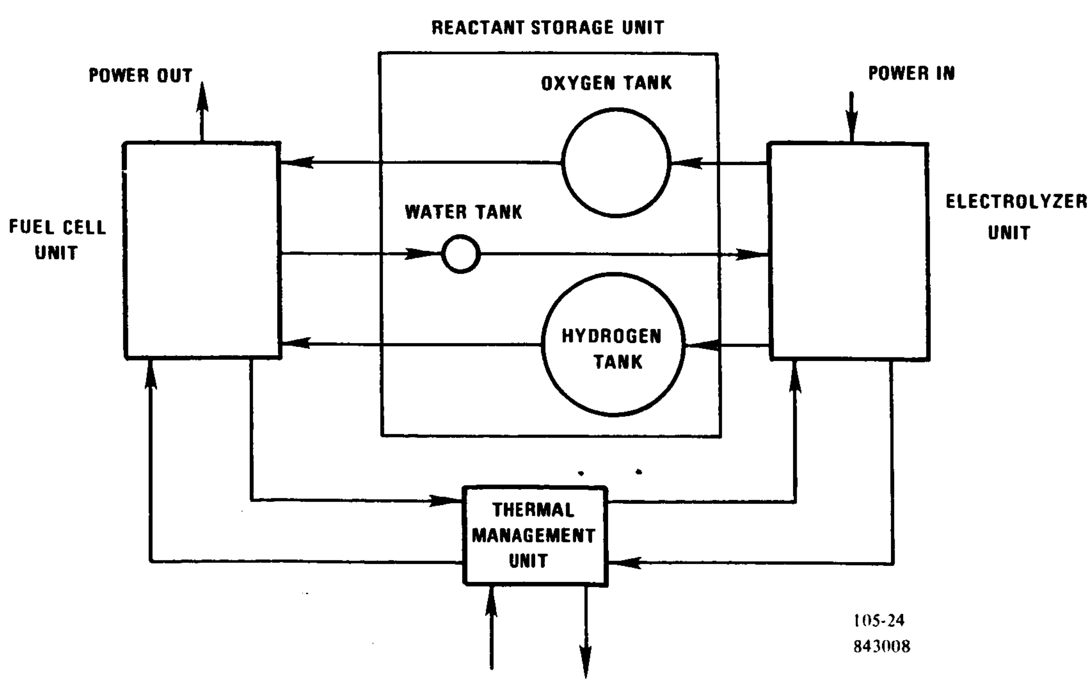

Figure 4. Regenerative Fuel Cell System Concept

B. System Operation

During the daylight portion of the orbit, the solar array provides power through a voltage regulator to the prime electrical bus system. In addition, the solar array supplies power through a power conditioner to the electrolysis cell module. The electrolyzer unit generates oxygen and hydrogen for subsequent use in the fuel cell unit by the electrochemical decomposition of fuel cell product water. The electrolyzer-produced reactants are stored in reactant storage tanks. Waste heat from the electrochemical reaction is removed from the electrolyzer unit by a liquid dielectric coolant loop.

In the occulted portion of the orbit, the fuel cell unit supplies power to the electrical bus by the electrochemical recombination of hydrogen and oxygen. Regulation of the fuel cell unit power supplied to the vehicle bus may be unnecessary because of the performance characteristics of the alkaline electrolyte fuel cell. Fuel cell product water, for subsequent use in the electrolyzer, is stored in the water storage tank.

A liquid dielectric coolant loop removes waste heat from the fuel cell modules and the electrolyzer during operating periods. For standby this loop provides heat to the idle unit to maintain operating temperature. In the isolation heat exchanger, waste heat is transferred from the coolant to the space radiator coolant loop. Waste heat from the system radiates to space from this radiator.

C. Baseline System

The baseline system chosen for detailed evaluation in this study resulted from a consideration of several potential system arrangements and a detailed evaluation of specific methods of managing the fuel cell product water and electrolysis cell product gases. A detailed review of these evaluations is included in Appendix A.

The baseline system is shown in Figure 5. It is composed of a fuel cell unit, an electrolyzer cell unit, a reactant storage unit, and a thermal management unit.

1. Fuel Cell Unit

The fuel cell unit is composed of a fuel cell power section, condenser, recirculating hydrogen loop including a hydrogen pump/water separator, demand type reactant pressure regulators, and a coolant loop including a coolant pump, coolant heater and oxygen pressure referenced accumulator. These components are arranged as shown in Figure 5.

Reactants are supplied to the power section from the reactant storage unit by a demand type reactant pressure regulator. These valves assure that the reactant pressure within the power section is maintained over the full range of reactant flows.

Product water is removed by the dynamic water removal method. Product water evaporates into the circulating hydrogen stream which carries it out of the power section. The water-laden hydrogen stream passes through a condenser, where the product water is condensed. It is then separated from the hydrogen stream by a dynamic water separator and delivered to the water storage tank in the reactant storage unit.

Waste heat is removed from the power section by circulating a liquid dielectric coolant through the condenser and through cooler assemblies within the power section. The fuel cell waste heat is rejected through an interface heat exchanger in the thermal management unit.

The fuel cell unit weight relationship used in the analysis includes the weight for a complete system, that is, power section, pumps, controls, instrumentation, insulation, and structure.

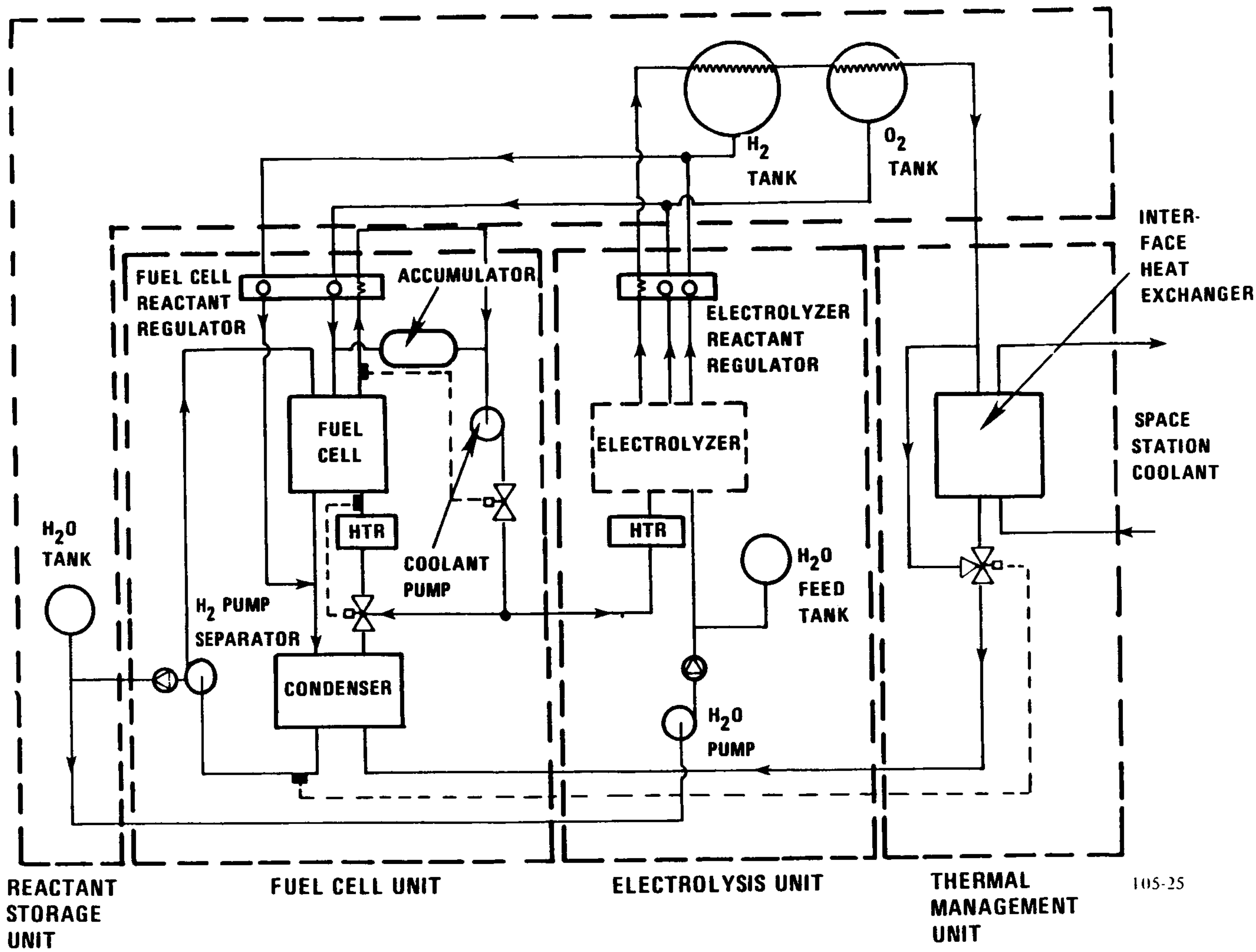

Figure 5. Regenerative Fuel Cell System Module Schematic

2. Electrolyzer Unit

Either of two types of electrolysis cells can be used in the electrolyzer unit. One is an alkaline electrolyzer utilizing static water feed while the other is an acid solid polymer electrolyte electrolyzer utilizing circulating water feed. Each is described below. The remainder of the components in the electrolyzer unit include demand type reactant pressure regulators, water feed pump, water feed tank, and coolant loop heater.

a. Alkaline Electrolyzer - The alkaline electrolyzer, shown in Figure 6, consists solely of an electrolysis cell stack utilizing an alkaline (KOH) electrolyte. Liquid water is pumped from the water storage tank in the reactant storage unit by the water feed pump into a liquid water cavity within each electrolysis cell. There it is electrolyzed into hydrogen and oxygen gas. The product reactant gases, laden with water vapor at a partial pressure in equilibrium with the electrolyte at cell temperature, exit the cell and are delivered via the pressure regulators to the storage tanks in the reactant storage unit. Temperature control is accomplished by passing the same dielectric coolant stream used in the fuel cell through coolers in the electrolysis cell stack.

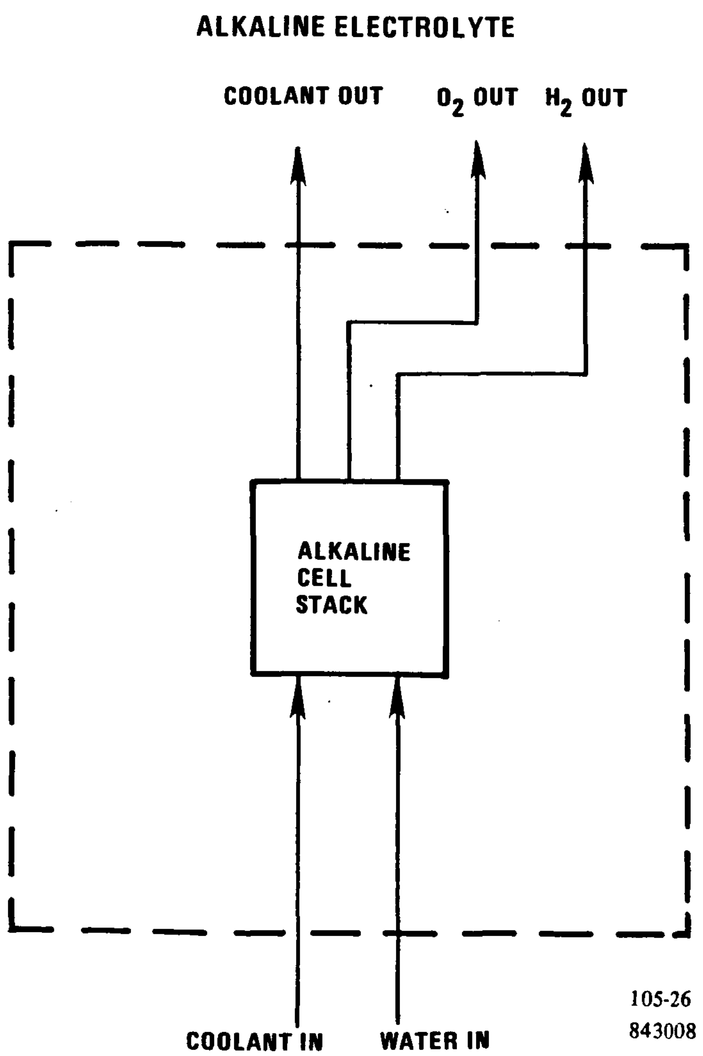

Figure 6. Electrolyzer Option - Alkaline Electrolyte

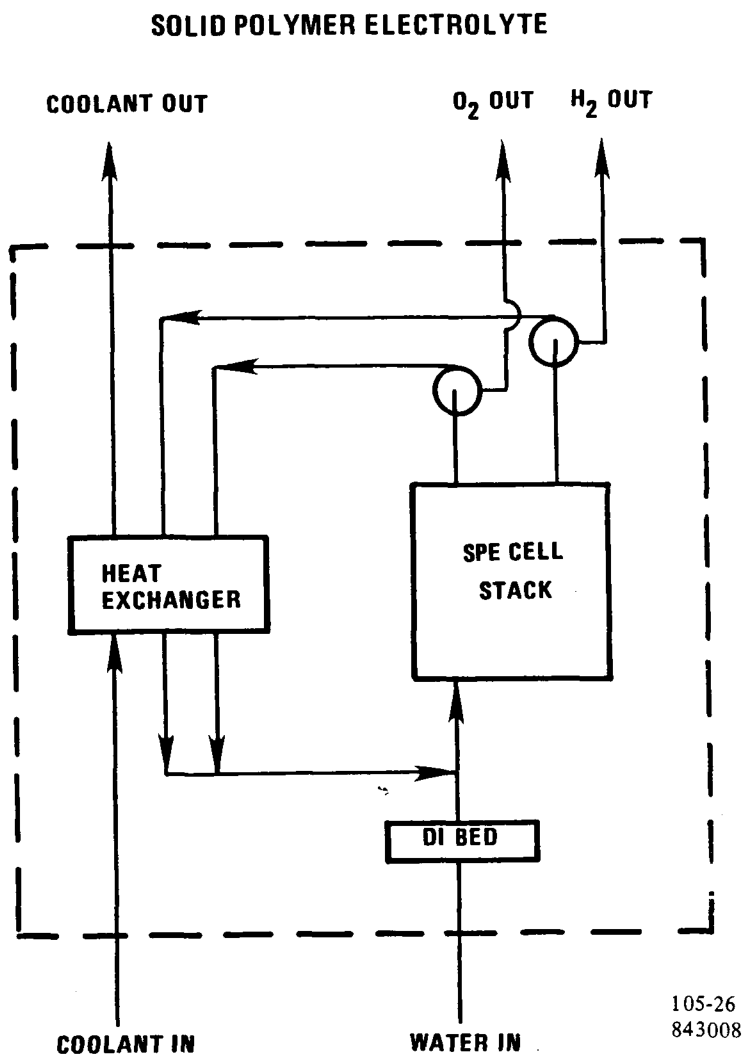

Figure 7. Electrolyzer Option - Solid Polymer Electrolyte

b. Acid SPE Electrolyzer - The acid solid polymer electrolyte (SPE) electrolyzer is depicted in Figure 7. It consists of a cell stack utilizing an acid ion exchange membrane electrolyte, anode and cathode water circulating pump/separators, a three fluid heat exchanger, and a water deionizer bed.

Liquid water is pumped from the water storage tank in the reactant storage unit by the water feed pump through the deionizer bed into the water recirculation loop. The water recirculation loop feeds the water into the cell stack on the anode side of each cell. Some water passes across the ion exchange membrane forming a second water loop. Thus, as electrolysis proceeds, an oxygen rich water stream exits the anode of each cell and a hydrogen rich water stream exits the cathode of each cell. Each of these streams pass through recirculating pumps which also act as separators for each reactant gas. The separated reactant gases are fed to the storage tanks in the reactant storage unit. The two water streams pass through a heat exchanger where waste heat is removed (or heat added if required) by the same dielectric coolant stream used in the fuel cell. The water streams are then merged and returned to the stack.

3. Reactant Storage Unit

The reactant storage unit comprises the tankage and associated components needed to store the gaseous reactants produced by the electrolyzer during the charge cycle and the liquid water produced by the fuel cell during the discharge cycle. Figure 5 depicts the arrangement schematically.

During the charge cycle, the electrolyzer produces gaseous hydrogen and oxygen each with a significant partial pressure of water vapor. In this regenerative fuel cell system, the gases are stored in reactant tanks in which the pressure varies initially from about 70 psia (48.3 N/cm^3) at the beginning of the cycle to slightly below the electrolyzer operating pressure at the end of the cycle. If an alkaline electrolyzer is used, the dew point in these gases is about 165°F (73.9°C) for a 180°F (82.2°C) nominal operating temperature, and if an acid solid polymer electrolyzer is used the gases are nearly saturated with water vapor.

As is explained in Appendix A, it was decided to prevent condensation of the water vapor in the reactant gases by maintaining the temperature of the piping and tanks above the dewpoint. In the baseline schematic, this is shown to be accomplished by utilizing the waste heat from both the fuel cell stack and electrolyzer stack and thus integrating the tank heaters into the system coolant loop. This arrangement is satisfactory so long as the tanks are reasonably close coupled with the rest of the system. In the event the tanks are remotely located from the system, it may be necessary to heat them electrically. It may also be necessary to heat trace the interconnecting piping.

It should be noted that it was assumed that all the reactant storage tanks and piping are insulated to minimize heat loss. The insulation recommended for a vacuum environment with a 20°R (11.1°K) sink is a 2 inch thickness of a gold metalized Kapton film/borosilicate microfibermat composite or equivalent. This degree of insulation can limit the heat loss from even the large hydrogen tank to about 10-20 Btu/hr (2.5-5.0 Cal/hr).

Fuel cell water is stored in a small bladder tank pressure referenced to the fuel cell recirculating hydrogen loop. The use of hydrogen rather than oxygen as the tank pressurant overcomes the potential of mixing hydrogen and oxygen should the tank bladder fail. The bladder is fitted with a position indicator to provide quantity measurements. Temperature control of the water storage tank is not viewed as critical, and heat loss is simply minimized, as noted above by the use of insulation on the tank and piping.

4. Thermal Management Unit

The thermal management unit is composed of the interface heat exchanger and its bypass loop. Because little is known at this time about the spacecraft coolant loop, (i.e., pressures, temperatures or flows available for system cooling), the heat exchanger cannot be specified. In all probability, it will be of an entirely conventional design. Flow through the bypass loop is controlled by a three-way valve which acts to maintain the fuel cell hydrogen condenser exit temperature.

IV. RFC SYSTEM CHARACTERISTICS

This section presents the results of the study to define the characteristics of a regenerative fuel cell system module. The items addressed are the module weight and volume, the module efficiency and the system reliability characteristics. The data is presented parametrically so that it can be used to conduct overall Space Station power system optimization studies.

A. Basis of Study

The technology and mission assumptions and groundrules that served as the basis of the study are shown in Table I.

The fuel cell performance and degradation rate are based on demonstrated operation of the Orbiter fuel cell power plant and testing of NASA-Lewis supported advanced fuel cell configurations at UTC. The documentation of these characteristics is presented in Section V. The weight of the fuel cell stack is based on an advanced cell package which is also described in Section V. The weights of the ancillary components, which service both the fuel cell and the electrolyzer, are based on Orbiter fuel cell power plant component weights with additional weight added to account for components specific to the electrolyzer. The parasite power is also based on Orbiter fuel cell power plant experience.

The electrolyzer performance and weight are based on data furnished to NASA by the electrolyzer manufacturers (References 15 and 16). These technologies are discussed further in Section V.

A single point comparison of the two electrolyzer technologies was made at an equivalent performance level and is shown in Table II. The equivalent performance of the two electrolyzers was accomplished by interpolating the solid polymer electrolyte (SPE) data to find the membrane thickness that yielded the same cell voltage at the same nominal current density. The resulting system efficiency is slightly higher for the alkaline technology and its module energy density is slightly lower than the SPE technology. Since the characteristics of the two electrolyzer technologies are very similar, it was decided to base the study on the alkaline technology thereby yielding more conservative weight values.

Table I. Basis of Study

Parameter	Fuel Cell	Electrolyzer
Technology		
Performance	Orbiter	NASA
Operating Temperature	140-180°F	140-180°F
Cell Performance Decay	2µV/Hr-Cell	0
Operating Pressure	60 psia	300 psia
Life	40000 Hours	40000 Hours
Weight Cell	NASA - LeRC Configuration	NASA
Components	Orbiter	
Parasite Power	1.7%	
Mission		
Duty Cycle (LEO)	Light Period Dark Period	58.8 Min 35.7 Min
Vehicle Power	100 kW	
Fuel Cell Voltage Regulation	120^{+10}_{-20} Volts	
Electrolyzer Input Voltage	100 Volts	
Other		
Kevlar® Wrapped Reactant Tanks		

Table II. Example Comparison of Anode Feed SPE Electrolyzer with Alkaline Electrolyzer

Nominal Power	10,000 watts
Nominal Temperature	140°F
Nominal Pressure	F/C = 60 psia E/C = 300 psia

Fuel Cell Operating Point

Gross Power (Watts)	10169
Number Stacks	1
Cells/Stack	124
Cell Area (Ft^2)	0.508
ASF	180.9
Vc (Volts)	0.893

Electrolysis Cell Operation Point, Weight and Volume

	Alkaline	SPE (17.5 mil IEM)
Gross Power (Watts)	11744	12019
Number of Stacks	1	1
Cells/Stack	56	56
Cell Area (Ft^2)	0.5	0.5
ASF	247	253
Vc	1.612	1.612
Faradic Efficiency	1.00	0.974
Weight (Lb)	203.5	156
Volume (Ft^3)	3.7	2.9
System Efficiency	.5097	.4961
Module Energy Density (W-hr/lb)	12.52	13.91

Since the power rating of the RFCS module for the Space Station is not defined, the rating was carried as an independent parameter in the study. For the same reason, the active area of the fuel cell and the electrolysis cell were allowed to change so that an optimum weight could be achieved. The weight relationship of the alkaline electrolysis cell stack was modified to incorporate the effect of cell area on stack weight. The relationship that was used is similar in form to that used for the fuel cell stacks.

B. Specific Weight

For a given fuel cell operating point (current density and cell voltage) there is only one electrolysis cell operating point that will result in a specified system efficiency. These operating points along with the power plant power, voltage and reactant requirements then determine the required cell areas, numbers of cells (both fuel cell and electrolysis cell) and ultimately module weight. A trade-off study of RFCS module weight and efficiency was conducted. By varying the fuel cell current density at several system efficiencies, it was determined that an optimum energy density could be identified. An example of such an optimization is shown in Figure 8.

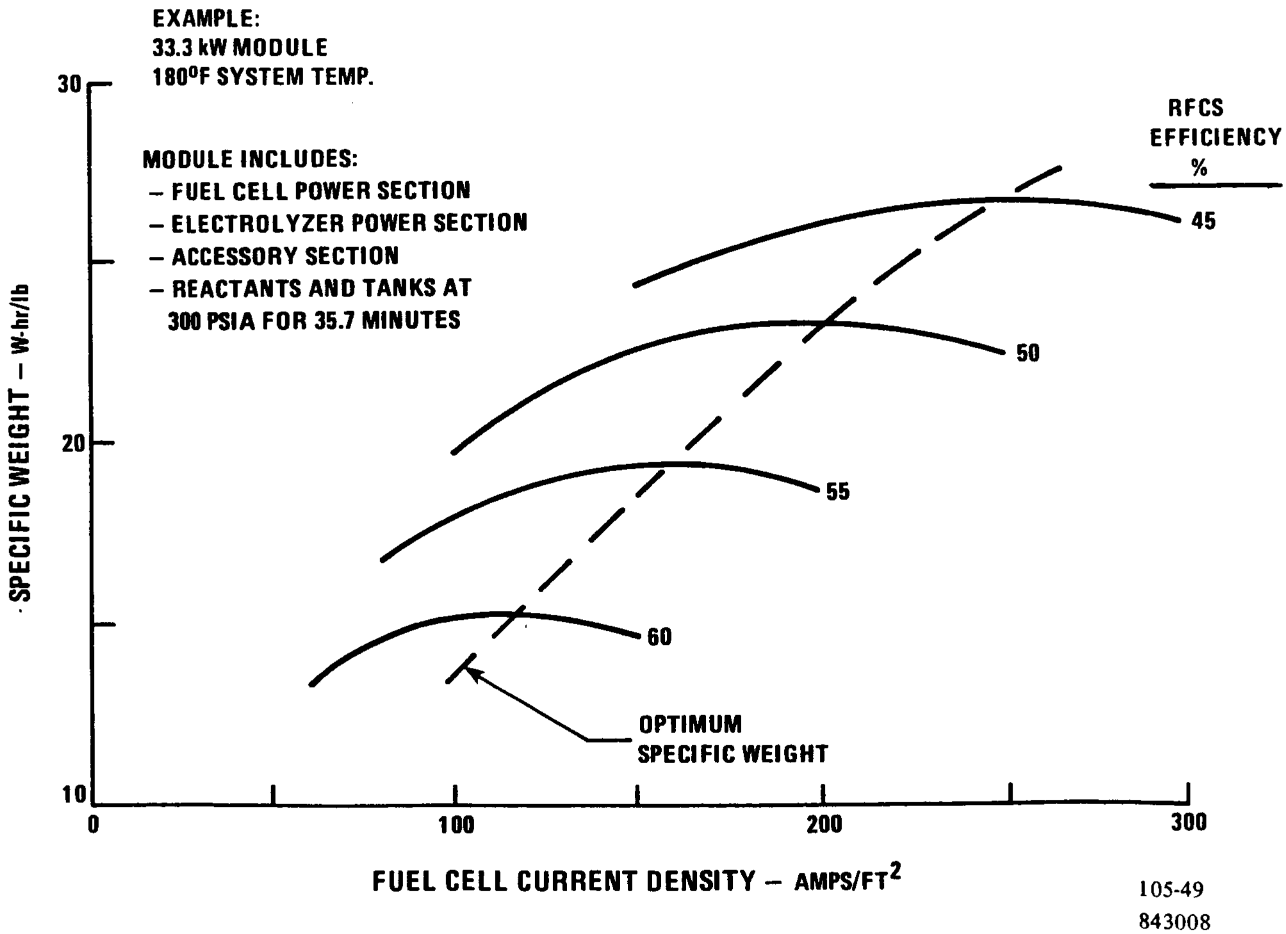

Figure 8. Specific Weight vs. Fuel Cell Current Density

The optimized specific weight of the RFCS module was determined as a function of the system efficiency and is shown in Figure 9 for four different power plant ratings. Three of these ratings (25, 33.3 and 50 kW) represent 1/4, 1/3 and 1/2 of the assumed total mission power of 100 kW, respectively. The 10 kW data is presented for reference. This data is representative of a system with the present technology fuel cells operating at a nominal cell inlet temperature of 140°F (60°C). It can be seen, for example, that a 33.3 kW module with a 50% efficiency would have an energy density of 19.8 watt-hrs/lb. At the same efficiency it can be seen that a 50 kW module would have a 7.5% higher energy density and a 25 kW module would have a 5.5% lower energy density.

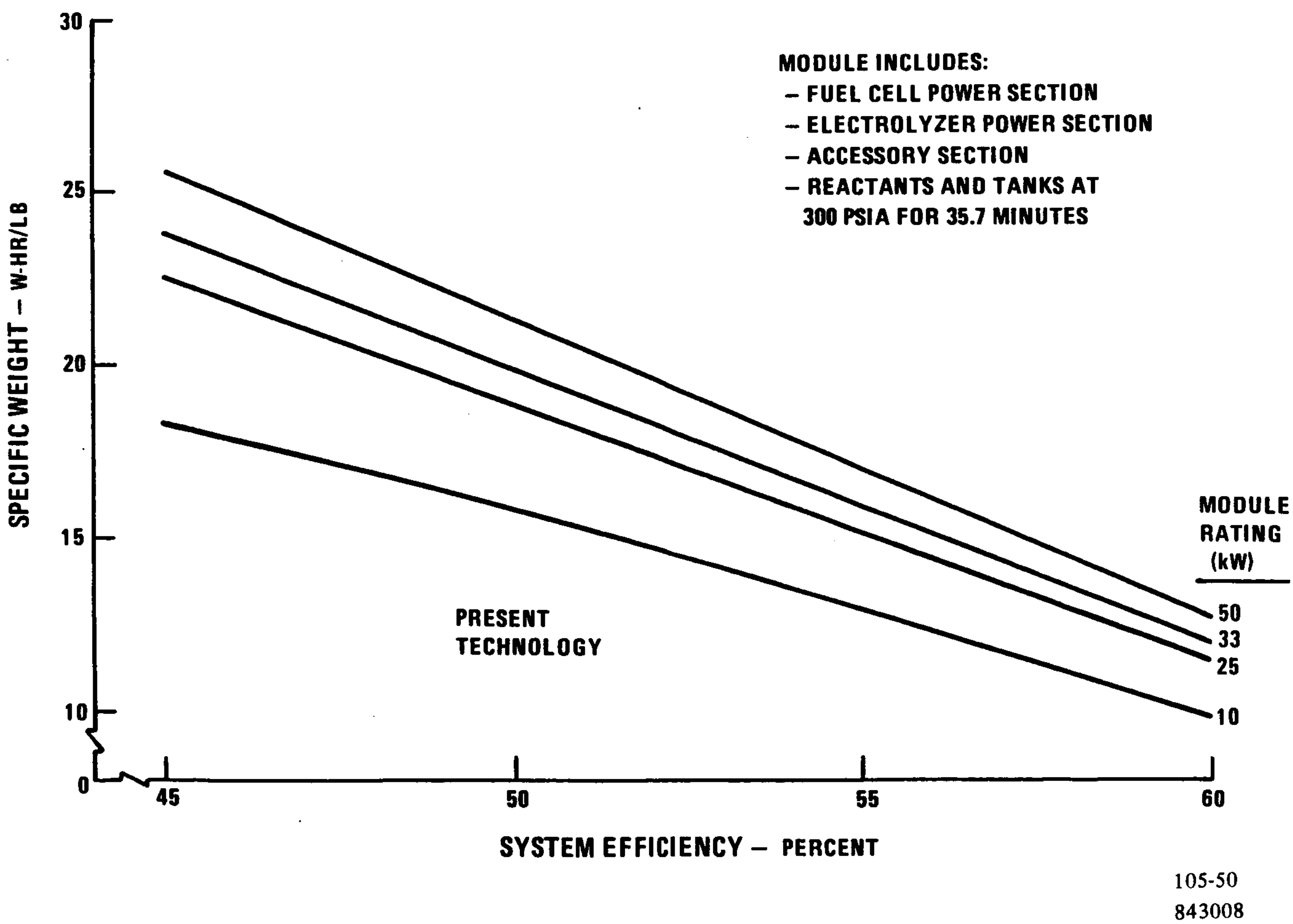

Figure 9. Specific Weight vs. Efficiency - Present Technology

With some development, the fuel cell will be able to achieve the same decay rate as the present technology (2µ volt/hr at 140°F (60°C)) while operating at a nominal cell inlet temperature of 180°F (82.2°C). The impact on specific weight of this development is shown in Figure 10. Increasing the system operating temperature for the same 50% efficient, 33.3 kW module results in an energy density of 23.2 watt-hours/lb. - an improvement of 17.2% over the present technology characteristics.

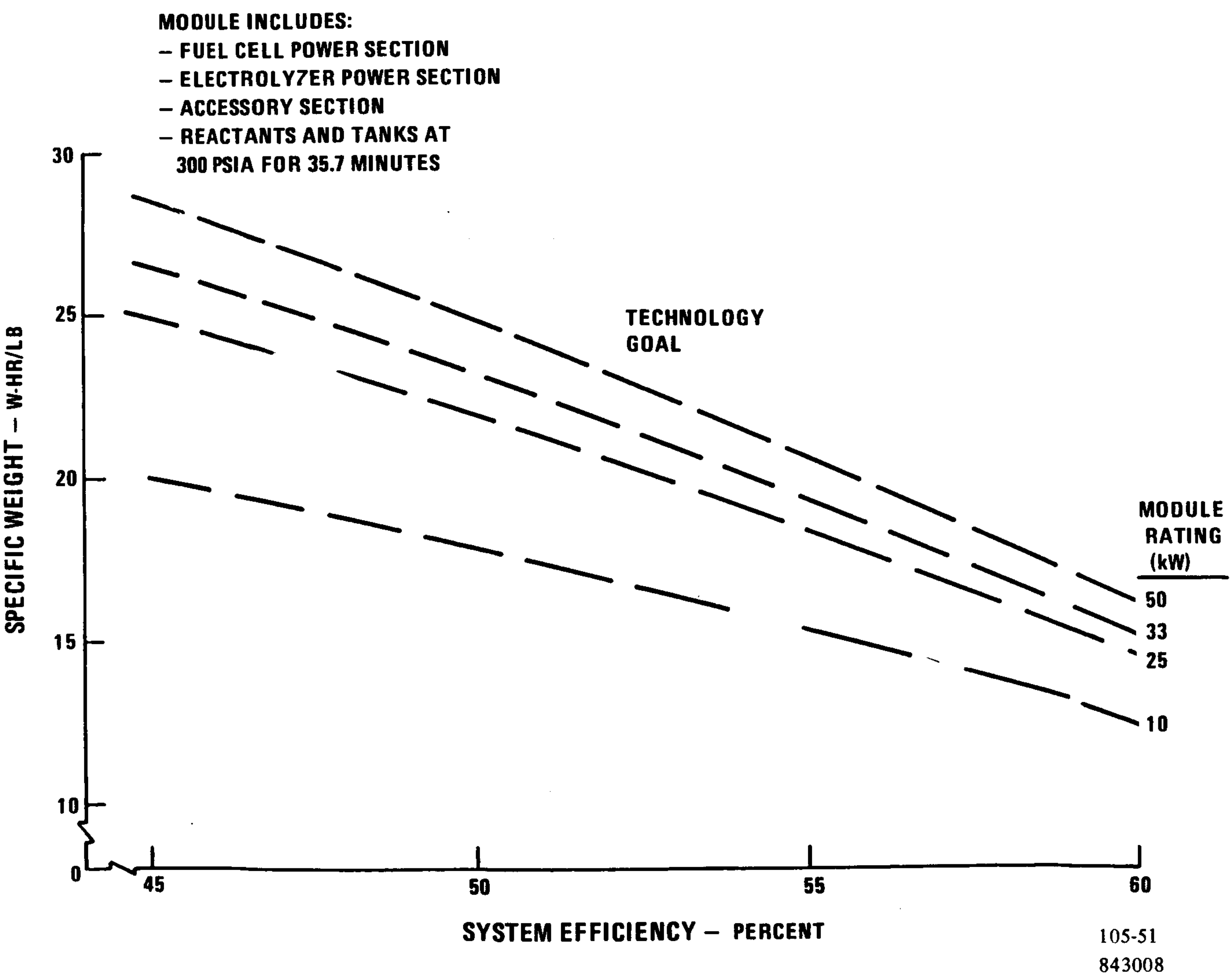

Figure 10. Specific Weight vs. Efficiency - Technology Goal

C. Specific Volume

The optimization described above was also done to determine the specific volume characteristic of the system. The results are presented in Figures 11 and 12 for the present technology and the technology goal, respectively. The minimum weight systems shown in Figures 9 and 10 are also the minimum volume systems so that the 50% efficient, 33.3 kW module that had a specific weight of 19.8 watt-hours/lb (Figure 9) will have a specific volume of 278 watt-hrs/ft³ (Figure 11). Similarly, the advanced technology power plant that had a specific weight of 23.2 watt-hrs/lb (Figure 10) will have a specific volume of 283 watt-hrs/ft³ (Figure 12).

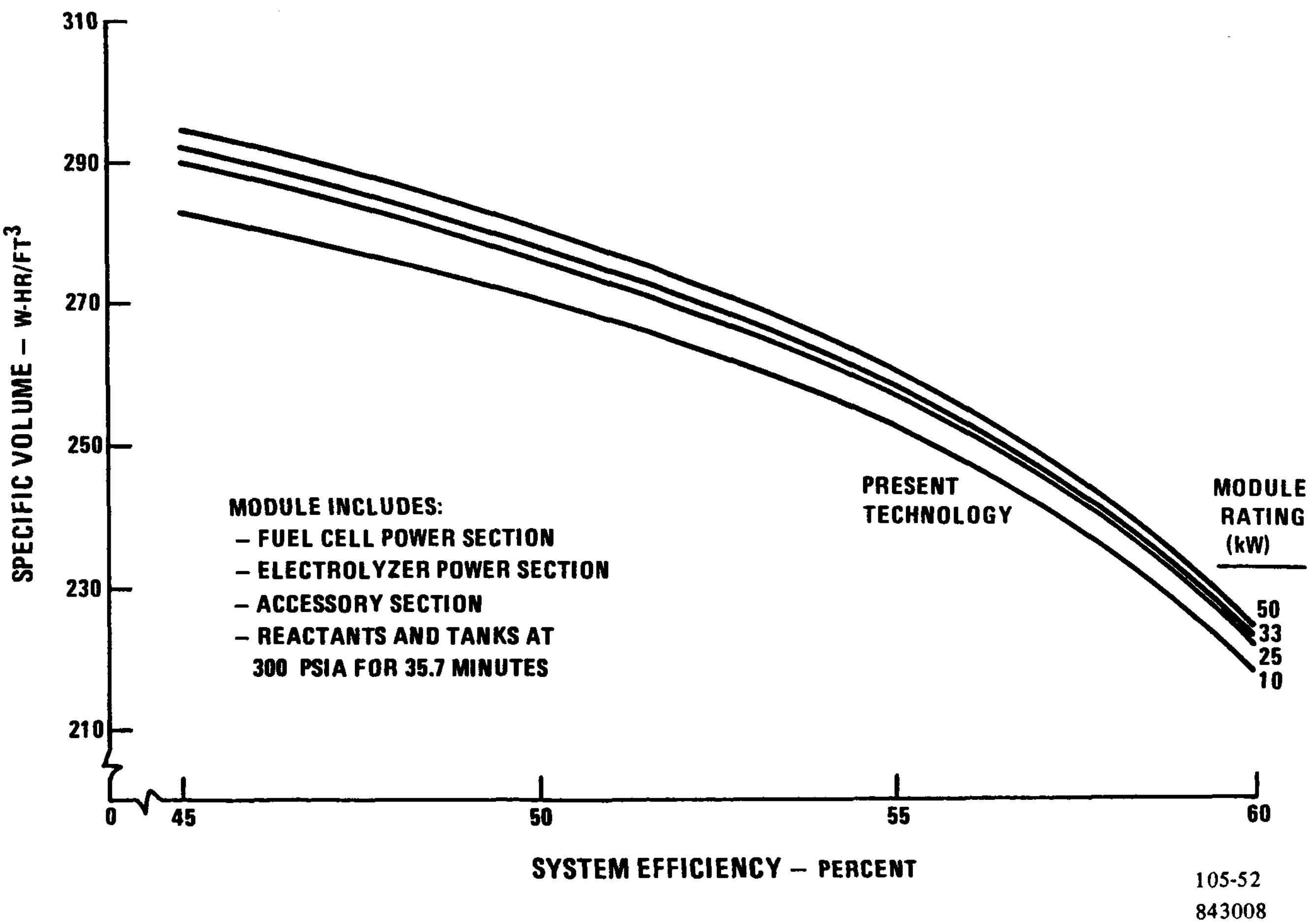

Figure 11. Specific Volume vs. Efficiency - Present Technology

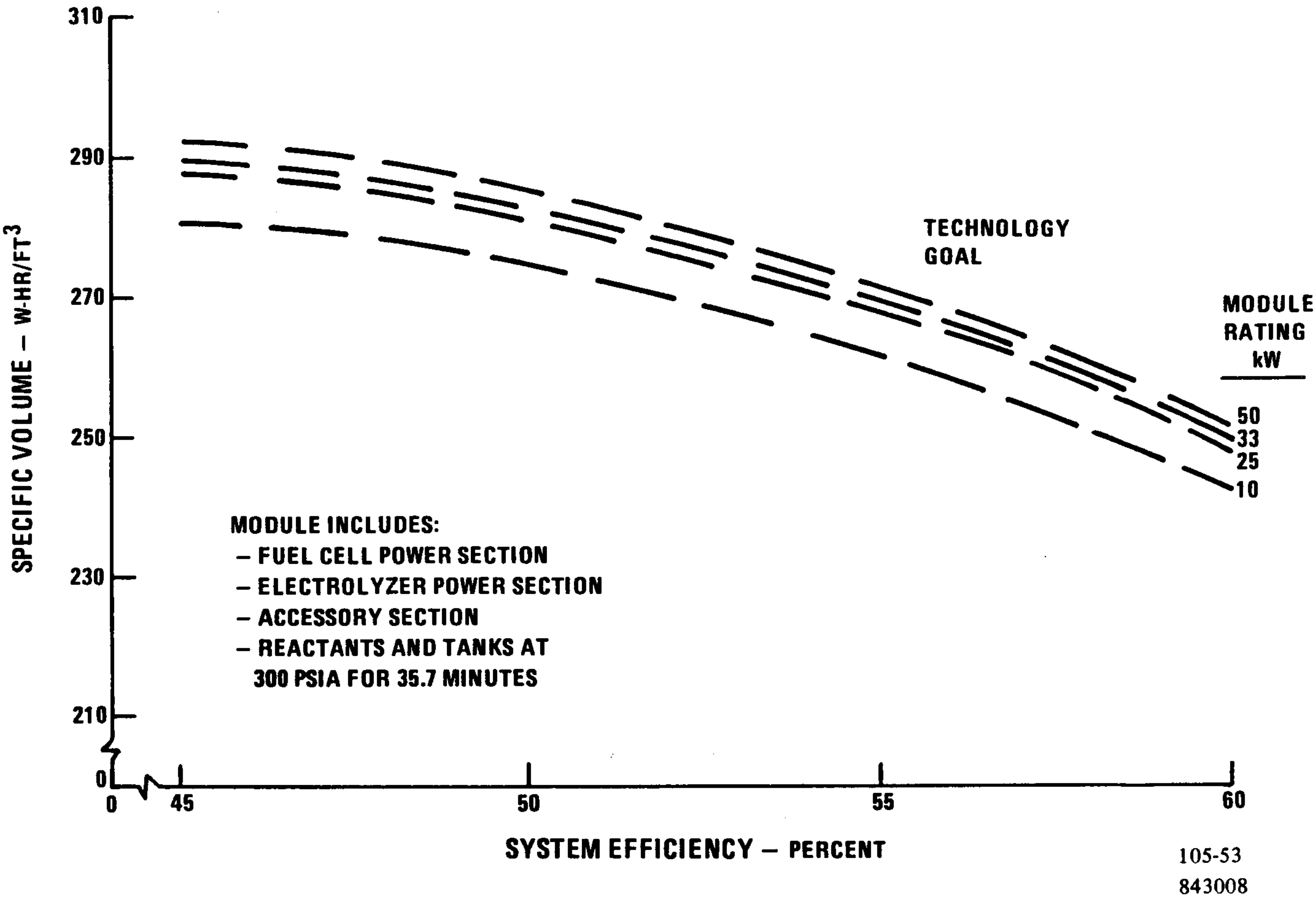

Figure 12. Specific Volume vs. Efficiency - Technology Goal

D. Emergency Power Capability

The weights and volumes indicated on Figures 9 through 12 include the fuel cell stack, the electrolysis cell stack, the accessory section, and reactants and tanks sized for an electrolyzer operating pressure of 300 psia and a fuel cell operating time of 35.7 minutes. A requirement for additional fuel cell operating time that might be imposed to accommodate emergencies, for example, can be easily met by storing extra reactants in the system reactant tanks. The impact on the reactant tank weight and volume for up to 5 hours of operation at rated power, is shown in Figures 13 and 14, respectively. This data is presented for a 33.3 kW module with the present technology (140°F operating temperature). The effect of system efficiency is included in the figures as well as the effect of increasing the electrolyzer operating pressure to 500 psia (344.7 N/cm²). Figures 15 and 16 show the impact of the improved technology (180°F (82.2°C) operating temperature) on these tank parameters. As can be seen a relatively small weight penalty is imposed for the extra capacity.

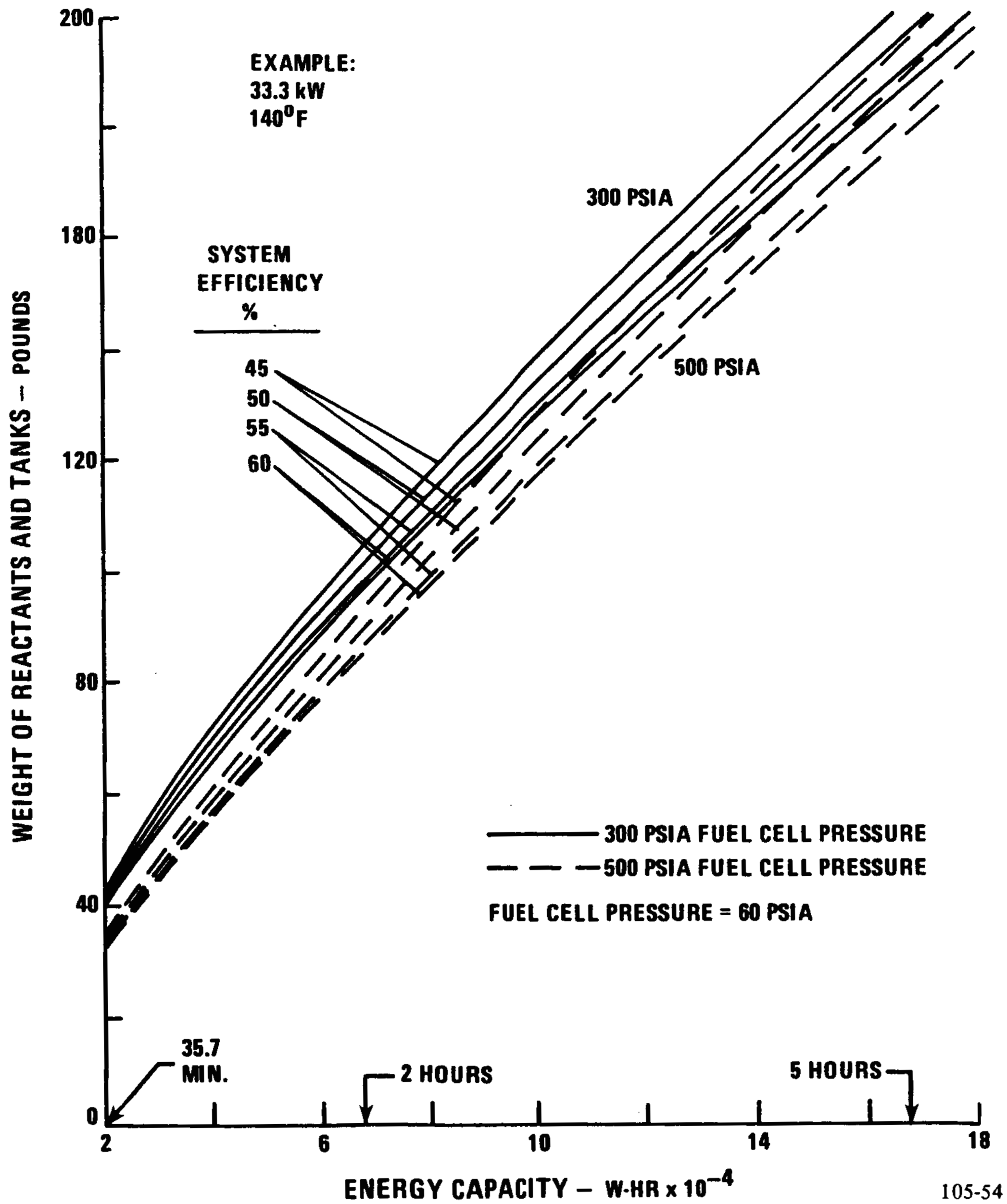

Figure 13. Sensitivity of Tank Weight to Pressure

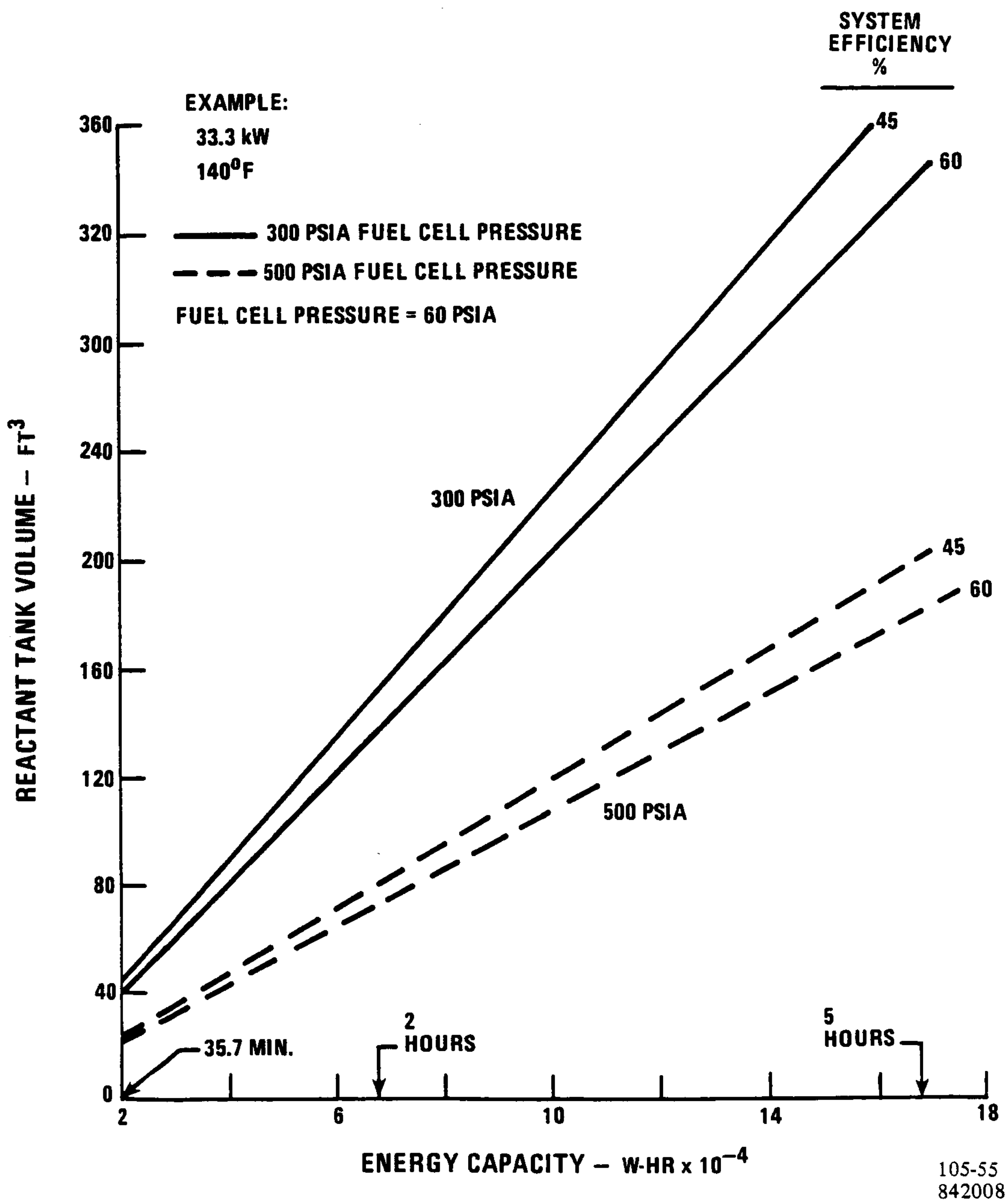

Figure 14. Sensitivity of Tank Volume to Pressure

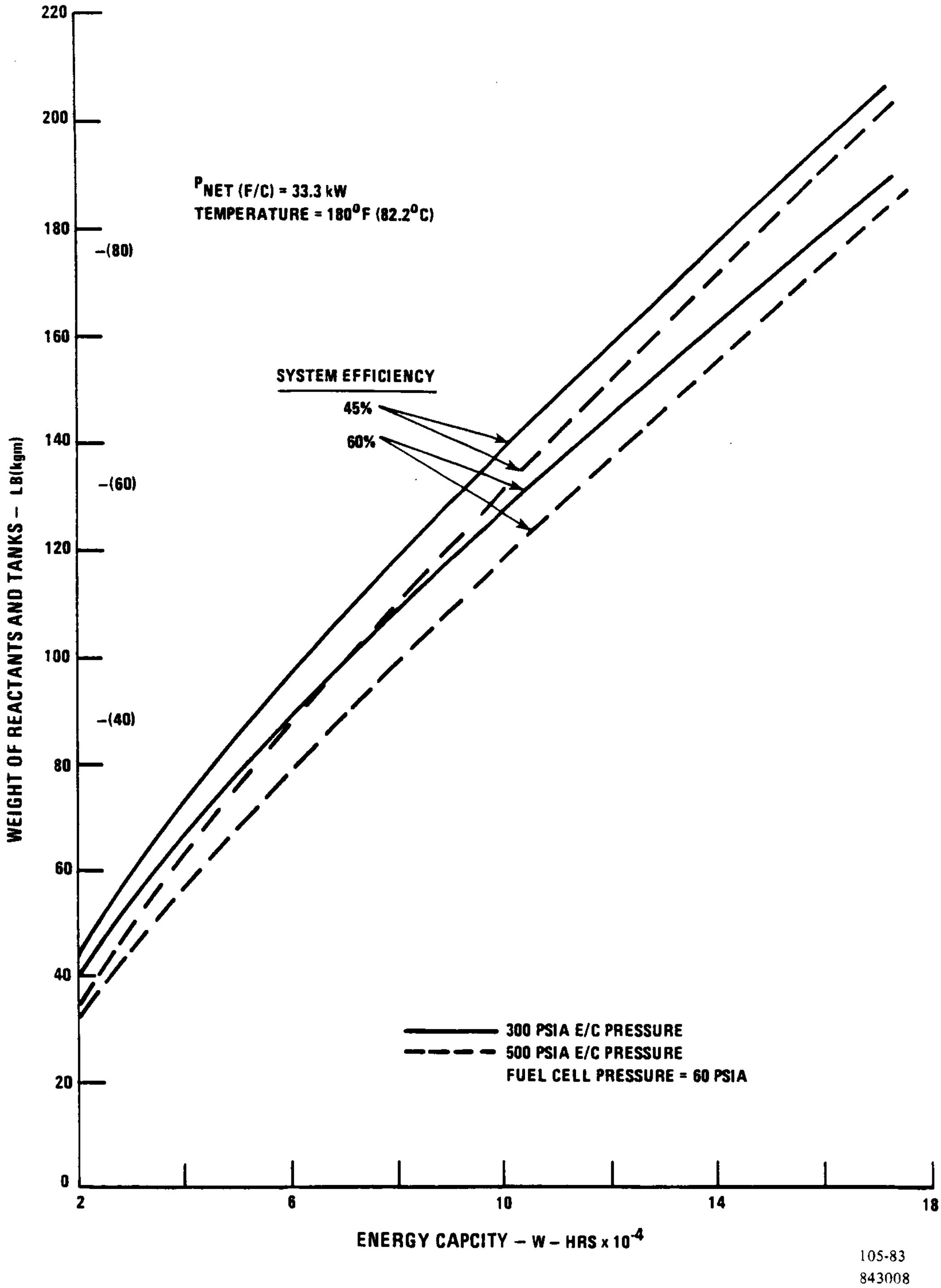

Figure 15. Reactant and Tank Weight as a Function of Energy Capacity

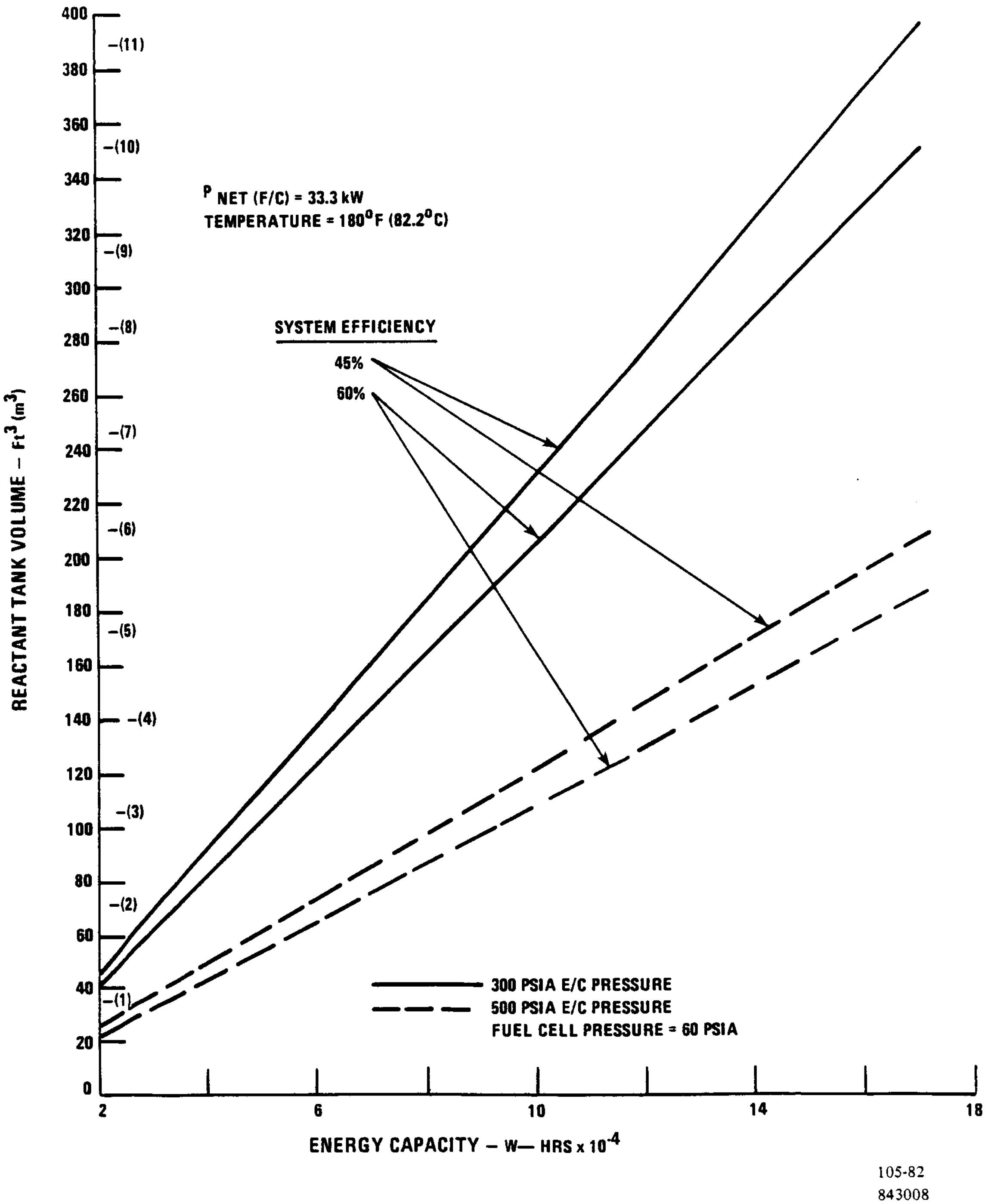

Figure 16. Reactant Tank Volume as a Function of Energy Capacity

E. Reliability and Maintenance

The importance of the RFCS to mission success and crew safety requires that reliability be the primary consideration. It also requires a careful consideration of maintenance philosophy and even affects the selection of module size. All these factors are discussed in this section because they are not mutually exclusive considerations.

The procedure used in dealing with these factors was as follows:

- A failure rate estimate was made for each component in the RFCS module and from this, an overall failure rate for the system could be determined.
- A maintenance approach was selected from several options.
- A module reliability was determined based on the selected maintenance approach.
- The number of spare RFCS modules required to meet the overall system reliability was determined.

Failure Rates

An RFCS module components list together with the estimated component failure rates is shown in Table III. The failure rates, which are based on random failures, were based on aerospace failure rate compilations (References 17 and 18) and from UTC failure data on electrochemical cells (Reference 19). It was assumed that the electrolysis cell stack failure rate is as good as that of the fuel cell stack. As shown below, the overall failure rate is estimated to be 69.31 failures per million hours.

Table III. RFCS Component/System Failure Rates

Fuel Cell Unit	λ, Failure Rate/10^6 Hours
Cell Stack (FCS-1)	7.00
Condenser (HEX-1)	1.11
H_2 Pump/Separator (PMP-1)	2.61
Coolant Pump (PMP-2)	2.900
Thermal Control Valve (TCV-2)	1.680
Stack Inlet Control Valve (TCV-1)	1.680
Start/Sustain Heater (HTR-1)	0.12
TCE Control Valve (TCV-3)	1.680
Coolant Accumulator (ACC-1)	0.400
Product Water Check Valve (CHV-1)	2.020
H_2 Pressure Regulator (PCV-1)	2.00
O_2 Pressure Regulator (PCV-2)	2.00
TCE Temperature Sensor (TE-6)	1.500
Coolant Return Temperature Sensor (TE-13)	1.500
Stack Inlet Temperature Sensor (TE-16)	1.500
Stack Exit Temperature Sensor (TE-17)	1.500
Pump Inlet Temperature Sensor (TE-18)	1.500
Electrolysis Cell Unit	
Cell Stack (ECS-1)	7.0
Water Feed Tank (TNK-4)	0.100
Water Feed Pump (PMP-3)	2.900
Water Check Valve (CHV-2)	2.020
H_2 Pressure Regulator (PCV-3)	2.00
O_2 Pressure Regulator (PCV-4)	2.00
Start/Sustain Heater (HTR-2)	0.12
Stack Inlet Temperature Sensor (TE-21)	1.500
Stack Exit Temperature Sensor (TE-22)	1.500

Table III. RFCS Component/System Failure Rates (Continued)

Reactant Storage Unit	λ, Failure Rate/10^6 Hours
H_2 Tank (TNK-1)	0.100
O_2 Tank (TNK-2)	0.100
H_2 Flow CTL Valve (FCV-1)	2.270
O_2 Flow CTL Valve (FCV-2)	2.270
H_2 Tank Pressure Sensor (PT-23)	1.700
O_2 Tank Pressure Sensor (PT-24)	1.700
H_2 Tank Coolant Temperature Sensor (E-23)	1.500
O_2 Tank Coolant Temperature Sensor (TE-24)	1.500
Product Water Tank (TNK-3)	0.100
Thermal Management Unit	
Interface Heat Exchanger (HEX-2)	1.11
Controller	5.00
Plumbing and Mechanical Parts	0.020
Frame and Mounting Support	0.100
	$\Sigma\lambda$ 69.31

The maintenance approach for the RFCS assumed in this study is complete module replacement coupled with earth-base module repair. A discussion of this and the other maintenance options that were considered is discussed in Section IV-F.

Reliability Requirements

With the complete module replacement maintenance approach, the system reliability is the probability of sufficient modules being available during a resupply period (replacement/repair turnaround period) to maintain the required minimum load. (As a baseline it was assumed that the full vehicle load was required.)

The reliability (R) of any given module is defined as:

$$R = \frac{\text{module uptime}}{\text{module uptime} + \text{module downtime}}$$

Module uptime is equivalent to the mean-time-between-failures as determined by the module failure rate. In this case,

$$\text{MTBF} = \frac{1 \times 10^6}{69.31} = 14428 \text{ hours}$$

Module downtime is the resupply period, assumed to be 30 days (or 720 hours) as a baseline. Thus,

$$R = \frac{14428}{14428 + 720} = 0.9525$$

As pointed out above, a single unspared module could not be expected to provide uninterrupted power for an extended period of time. The number of spare modules required to provide a reasonable system reliability goal, as yet undefined, is dependent on the number of modules required to meet the total space station load which is also undefined.

Fortunately, the matter can be handled parametrically. If k modules are required to meet the vehicle load and m modules are available (the number of spares being (m-k)), the probability of being able to meet the vehicle load may be expressed as

$$P = \frac{m!R^m (1-R)^0}{m!0!} + \frac{m!R^{m-1} (1-R)^1}{(m-1)!\ 1!} + \cdots + \frac{m!R^k (1-R)^{m-k}}{k!\ (m-k)!}$$

This relationship was used to determine the impact of several parameters on the RFCS reliability.

a. Module Rating - The total Space Station power requirement along with the module rating determines the number of modules required to operate for full power. For example, with a total power requirement of 100 kW and an individual module rating of 25 kW, four modules are required to generate full load. The impact of module rating on reliability is presented in Figure 17 for three different module ratings (1/4, 1/3 and 1/2 power) as a function of the number of spare modules on-orbit. Conversely, the number of spare modules required to achieve given reliability can be determined as a function of module rating. For example, with three modules required to meet full load, a 30 day resupply period, an MTBF of 14400 hours, and a system reliability goal of approximately 0.99, one spare module must be on-orbit. With a smaller module (four required to meet the same total load) and everything else the same, two spare modules are required because one spare is insufficient.

b. Resupply Period - The impact of resupply period on system reliability and spare modules is presented in Figure 18 for a system that requires three modules for full power. It can be seen that, with a reliability goal of 0.99, for example, one spare is required for resupply periods between 15 and 30 days, two spares between 30 and 60 days and three spares between 60 and 90 days.

c. Minimum Power Requirement - The probability (reliability) of supplying 100% of the space station power was presented above. If, however, it were acceptable to have less than 100% power, fewer spares might be needed. Again, for the example of a 1/3 size module (three modules required to meet full power), the impact of the

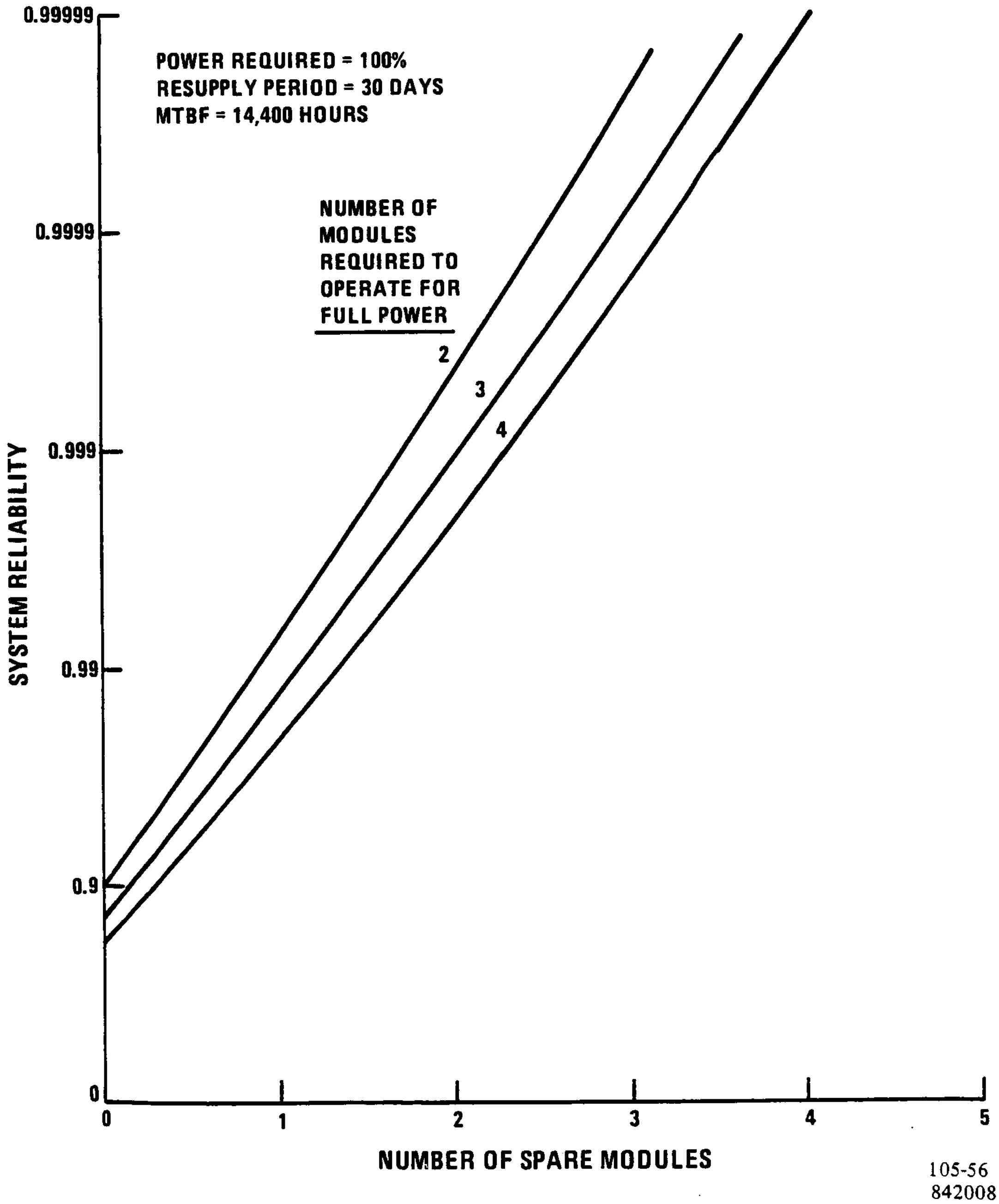

Figure 17. Impact of Module Rating on Reliability

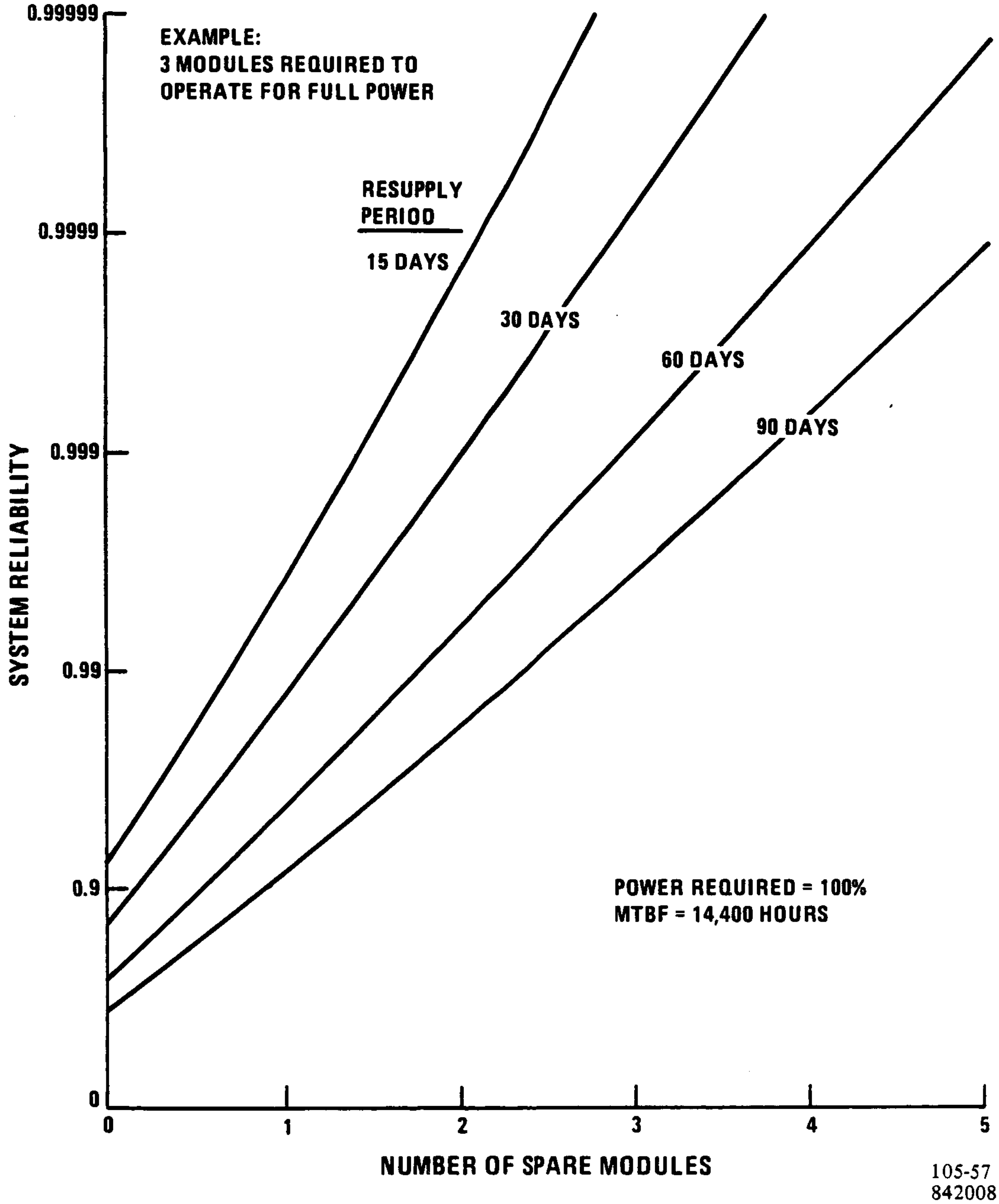

Figure 18. Impact of Resupply Period on Reliability

minimum power requirement on system reliability and number of spares is shown in Figure 19. It can be seen that, for a 0.99 reliability, two thirds of the total power can be delivered with no spares.

d. Mean-Time-Between-Failure - The MTBF used in the foregoing discussions (14400 hours) was based on the estimated failure rates of the individual components in the power plant. The impact of MTBF on the system reliability and the number of spare modules required is presented in Figure 20. A higher MTBF can be accomplished by simplifying the components and/or the module and/or installing redundant components within the module. Again, for the example of the three module case and a reliability goal of 0.99 it can be seen that increasing the MTBF from 14400 hours to 30000 hours does not eliminate the requirement for one spare. However, it does, of course reduce the number of failures and therefore the number of module replacements required during the mission.

e. Maintenance - The maintenance approach for the RFCS that was assumed for the reliability study described in the preceding section involved complete module replacement with earth-base repair. This selection was influenced by the assumption that, given the considerations stated below, complete module replacement would be the ultimate Space Station philosophy and that alternative approaches, either alone or in combination were too complicated to evaluate at this point in the definition of the regenerative fuel cell system.

In-space component replacement and/or repair would result in a lower total mission weight-to-orbit than complete module replacement. The ability to provide this maintenance however, requires an on-board workshop and special test facilities in which the replacements and/or repairs would be made and their success verified. In addition, the complexity of the system would increase because of the addition of the numerous fluid disconnects and isolation valving. The RFCS volume would also increase so that the components would be more accessible for in-space servicing. RFCS could be designed with this flexibility for in-orbit maintenance if the overall philosophy requires it.

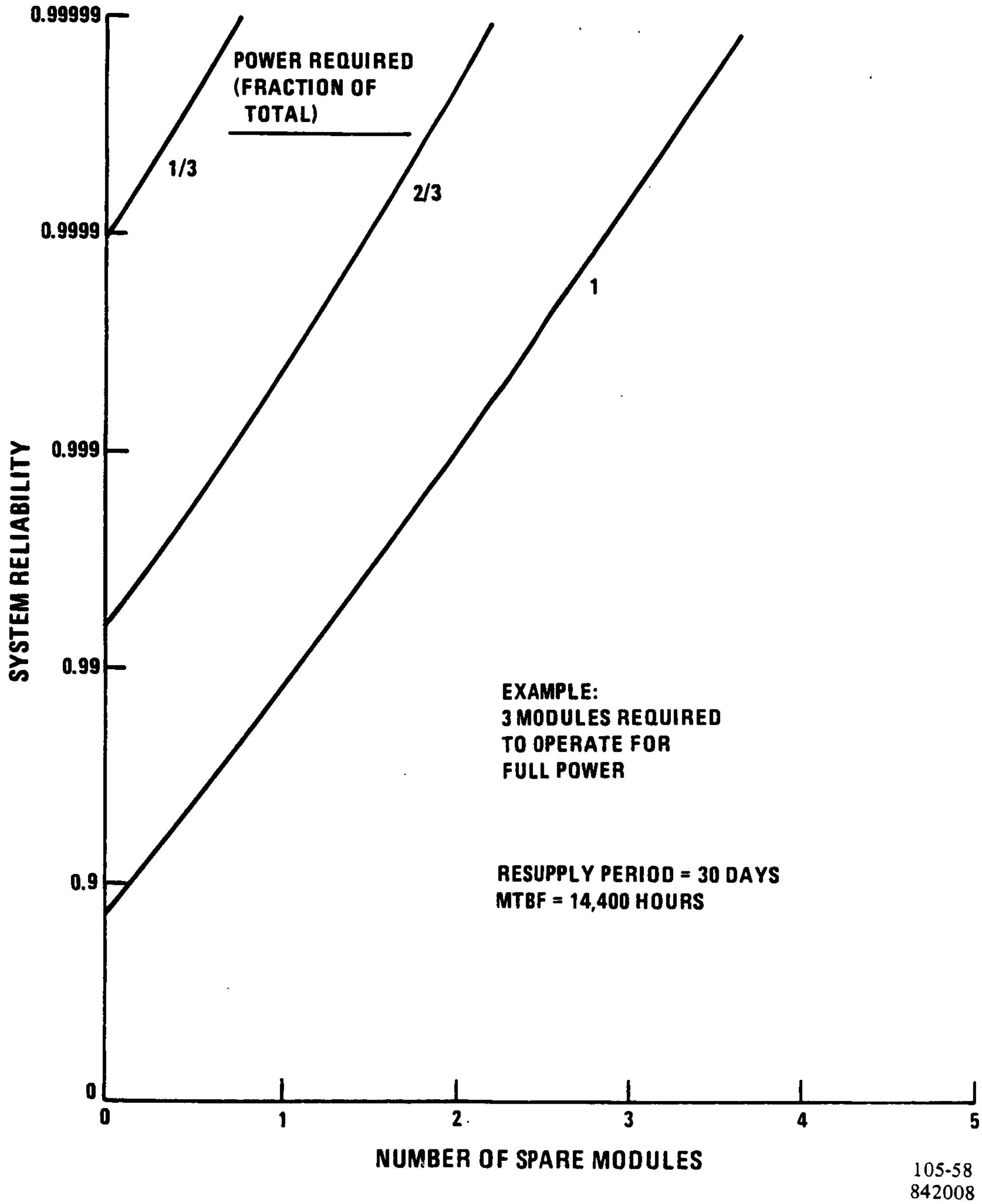

Figure 19. Impact of Minimum Power Required on Reliability

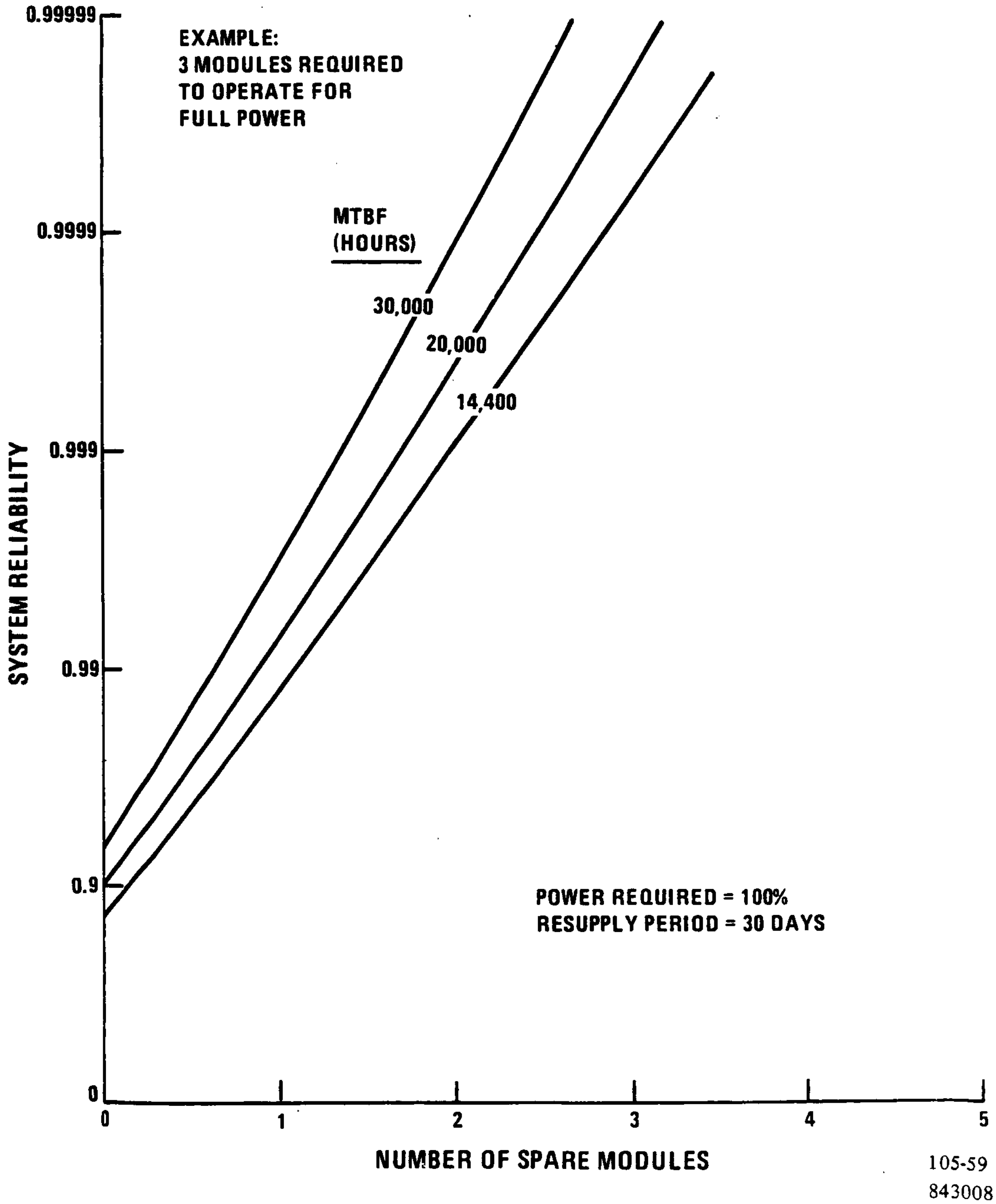

Figure 20. Impact of MTBF on Reliability

Another option for minimizing maintenance is to incorporate internal redundancy in the accessory package. The inclusion of redundant components within a RFCS module will not only result in a lower total mission weight-to-orbit but it has the potential for increasing the module MTBF which will increase the system reliability. In spite of the fact that the redundant component does increase the MTBF, provisions have to be made for sensing the failure of a component and, if desired, automatically switching over to the redundant component.

It can be seen that combinations of the maintenance approaches might provide a more optimum situation than any single one. Depending on mission requirements, redundant components with manual switchover after caution and warning signals might be acceptable. Certain components might be more easily replaced in space and therefore, would not warrant the return of the entire module. The selection of an optimum maintenance approach could be identified by an integrated logistics support (ILS) study when the RFCS is better defined.

V. PACING TECHNOLOGY

This section presents the basis for the Regenerative Fuel Cell System study, identifies the pacing technology issues for the fuel cell subsystem, electrolysis cell subsystem and ancillary components along with recommended demonstration tests, and specifies system integration tests required for the Engineering Model System (EMS).

BASIS OF STUDY

The technology status utilized as the Basis of Study for the Regenerative Fuel Cell System is presented in Table IV.

Table IV. RFCS Basis of Study

Technology Parameter		Fuel Cell	Electrolyzer
Performance		Orbiter	NASA
Operating Temperature		140-180°F	140-180°F
Cell Performance Decay		2 μV/hr-cell	-
Operating Pressure		60 psia	300 psia
Life		40,000 hours	40,000 hours
Weight	Cell	NASA - LeRC Configuration	NASA
	Components	Orbiter	-

Fuel cell characteristics are based upon Orbiter fuel cell power plant experience and technology advances resulting from the NASA-Lewis sponsored technology advancement program. A description of the fuel cell configuration, performance and endurance characteristics are presented in Section V.A.

The electrolysis cell characteristics for performance, volume and weight were provided to United by NASA. The characteristics for the alkaline electrolyte water electrolyzer are presented in Reference 15. Reference 16 summarizes the characteristics of the solid polymer electrolyte water electrolyzer cell.

A. Fuel Cell System

The fuel cell performance utilized in the study is presented on Figure 21. The performance is based upon Orbiter fuel cell power plant experience with a voltage level reduction consistent with the long-term simulated Regenerative Fuel Cell endurance test results shown on Figure 23. The endurance test conducted with a large-size six-cell stack has completed 18,000-hours of operation with a voltage reduction rate over the majority of the test of less than 2 microvolts per hour.

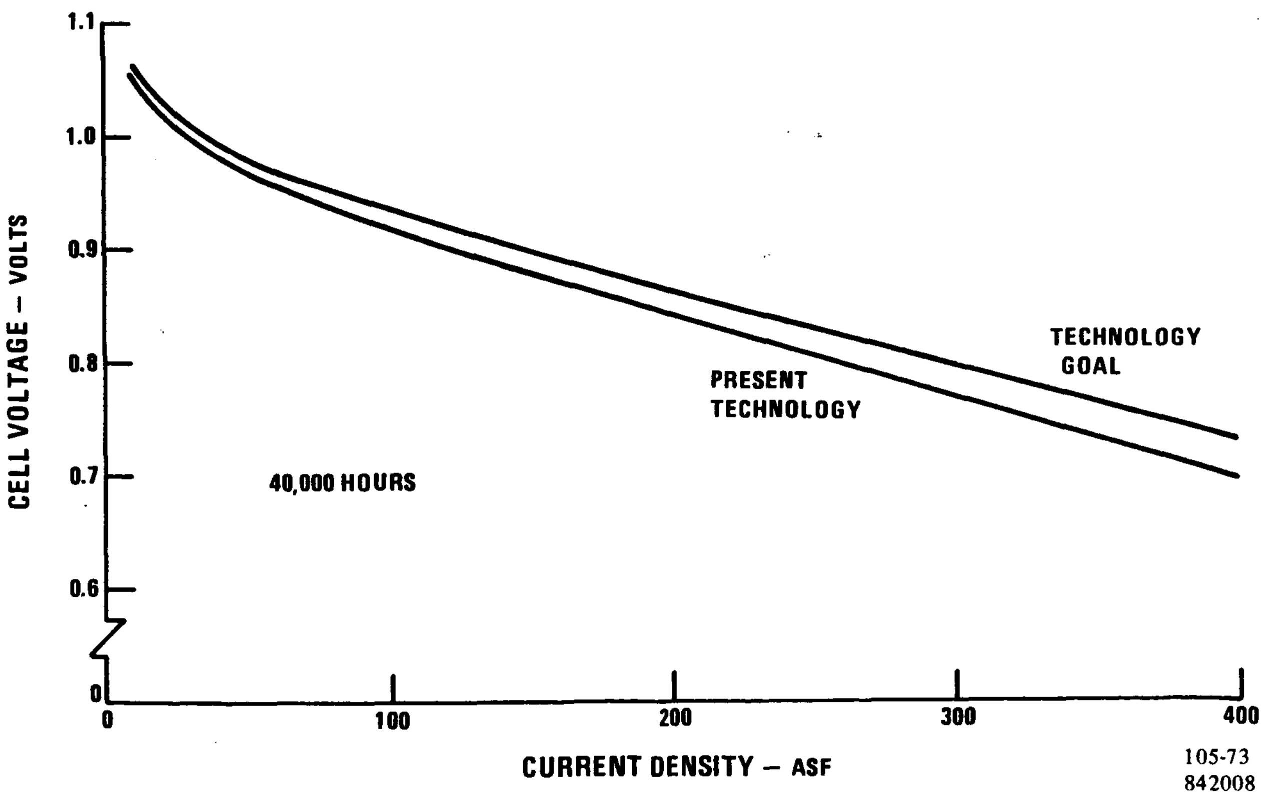

Figure 21. Fuel Cell Performance

The 40,000-hour performance is for a modified Orbiter fuel cell incorporating stable, long-life matrices, cell edge frames and electrodes identified under the technology advancement program. The present technology performance level represents a fuel cell operating at 140°F (60°C). The higher performance level or technology goal is for a fuel cell operating at 180°F (82.2°C).

The power generating unit of the fuel cell stack is the unitized electrode assembly shown in Figure 22. The unit consists of an hydrogen and oxygen electrode separated by an electrolyte-containing matrix, with a porous electrolyte reservoir structure adjacent to or integral to the anode. All these components are unitized into a structural edge frame which is fabricated of a plastic-reinforced structure.

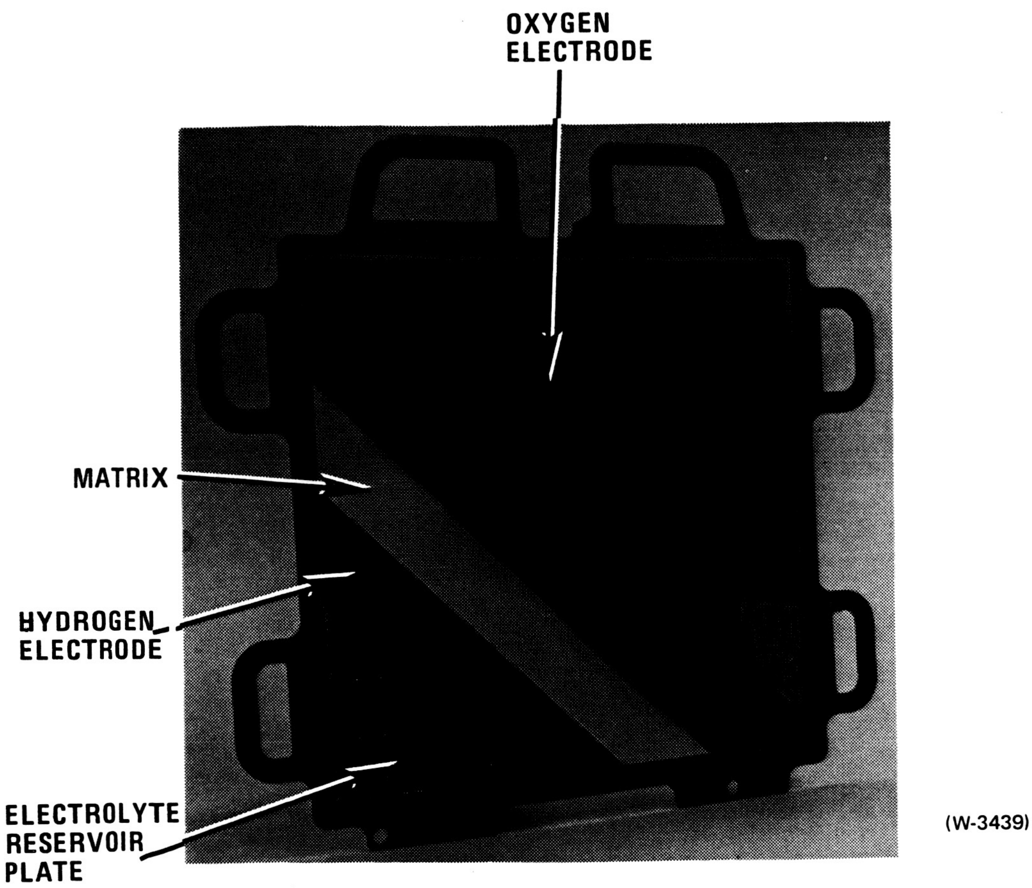

Figure 22. Fuel Cell Unitized Electrode Assembly

A technology base is being developed for application to the Regenerative Fuel Cell. A six-cell fuel cell stack comprised of Orbiter-type fuel cells has completed 18,000-hours (12,000 cycles) of cyclical operation.

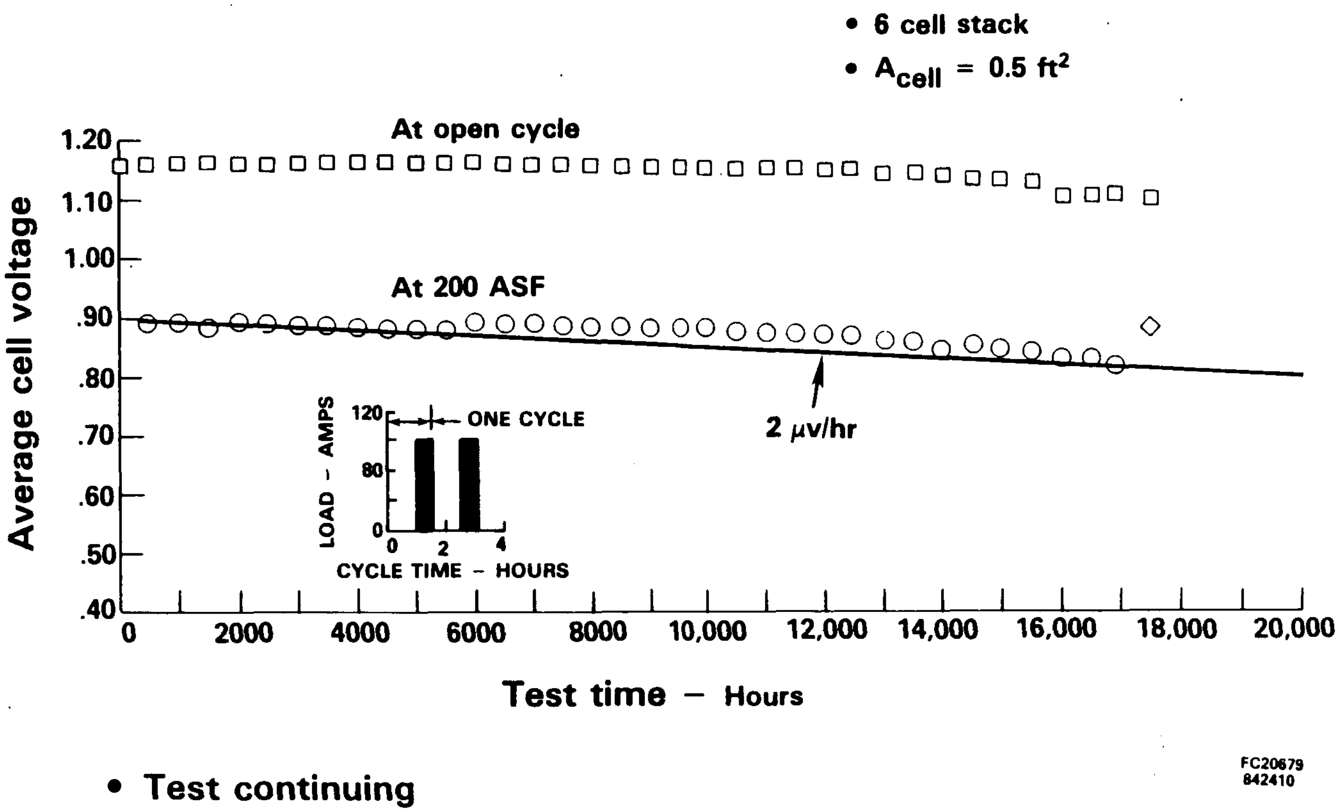

Figure 23. Regenerative Fuel Cell Endurance Test

The initial performance of this first six-cell stack tested to a cyclical load profile was lower than expected. Recent stack test experience however has demonstrated performance levels consistent with Orbiter experience. A recently constructed four-cell stack incorporating cells with corrosion-resistant potassium titanate matrices, see Figure 24, and lightweight graphite electrolyte reservoir plates, shown on Figure 25, has completed over 3000-hours of operation. The performance history of the four-cell stack being endurance tested under the Lewis program is shown on Figure 26.

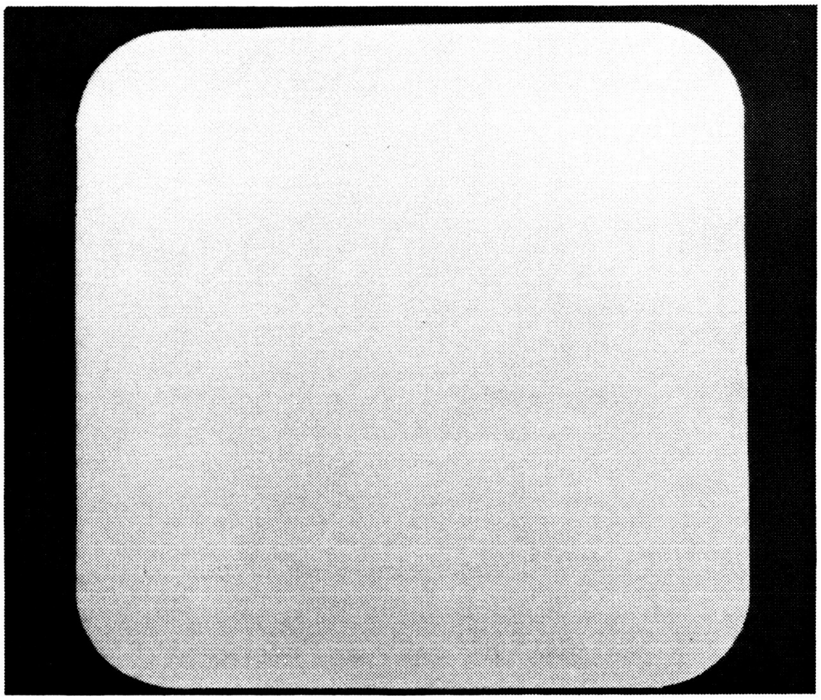

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Figure 24. Butyl Rubber Bonded Potassium Titanate Matrix

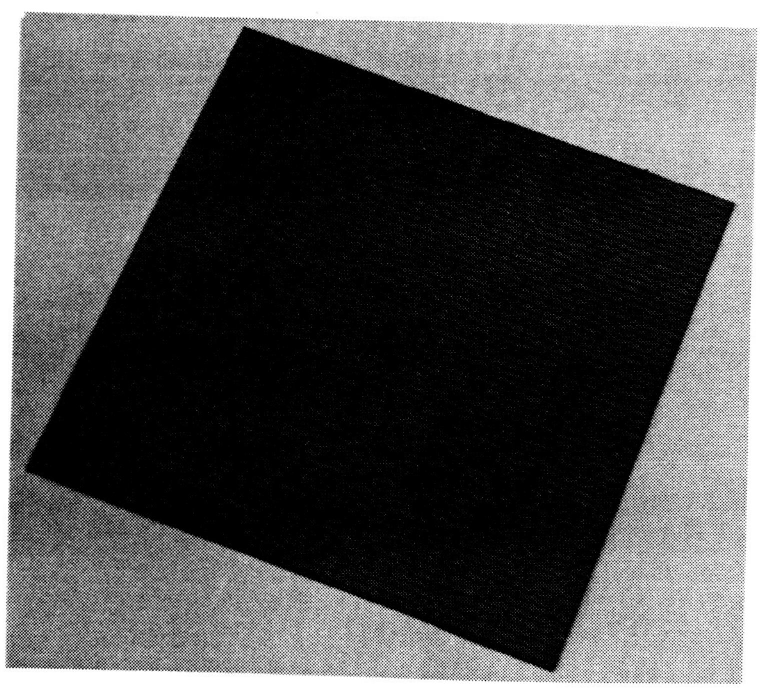

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Figure 25. Graphite Electrolyte Reservoir Plate

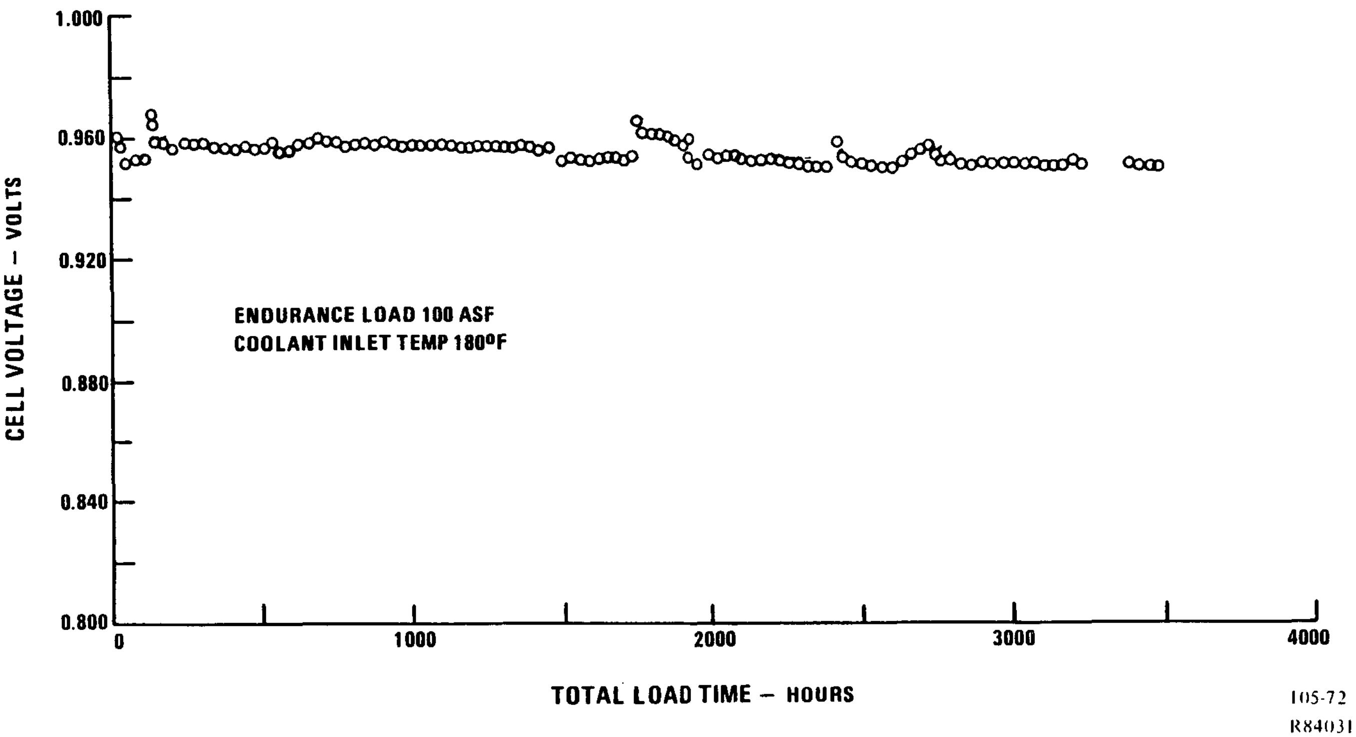

Figure 26. NASA-Lewis Four-Cell Stack Endurance Task

A four-cell stack incorporating all of the cell features contained in the previously described four-cell stack plus a corrosion-resistant molded cell edge frame shown in Figure 27 and lightweight cooler assembly has completed over 3000-hours of testing with no overall reduction in cell performance. The stack was constructed and is being endurance tested under a Navy program. The endurance test will be continued under a United IR&D program. The performance history of the stack is shown in Figure 28.

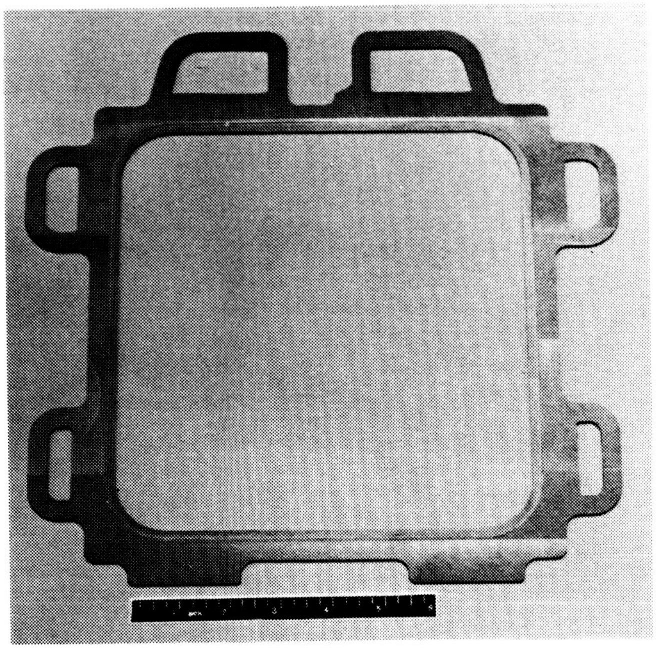

Figure 27. Molded PPS Cell Edge Frame

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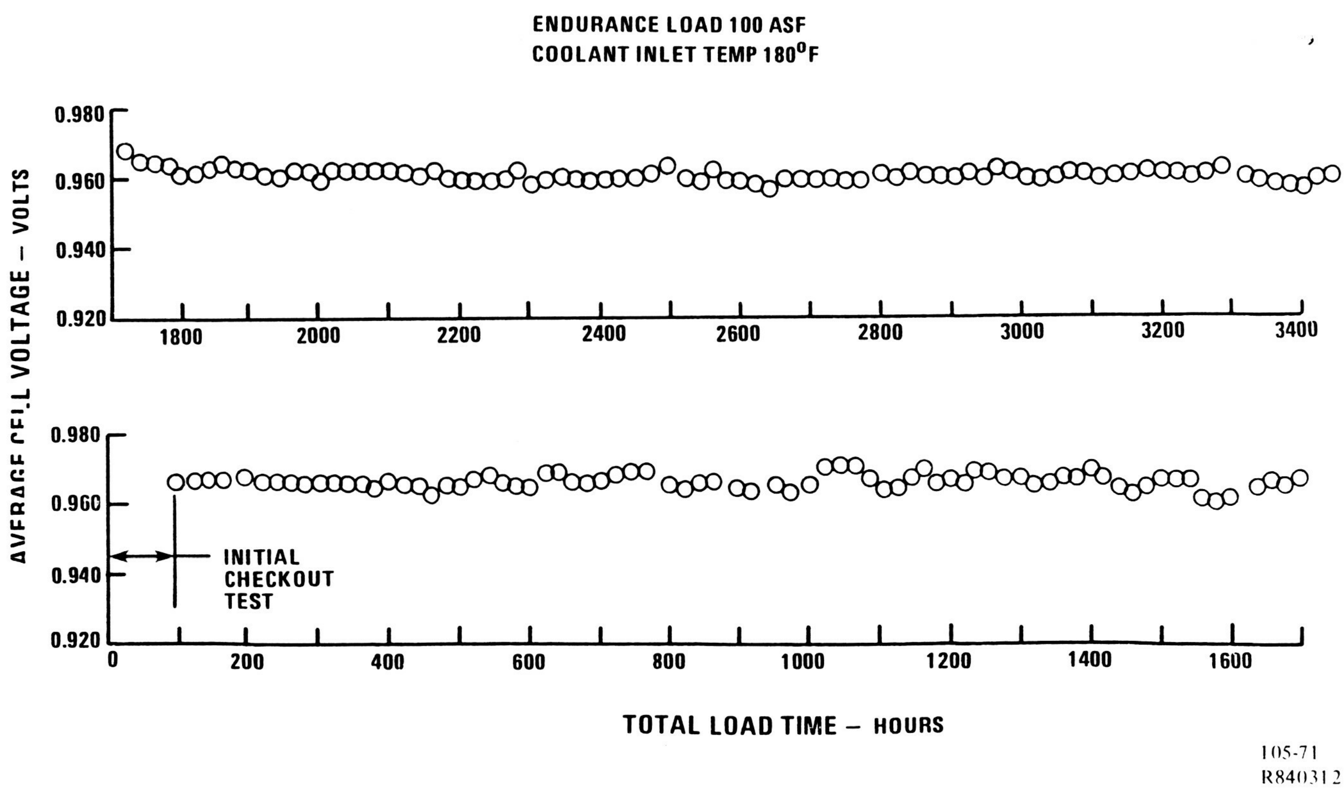

Figure 28. Navy Four-Cell Stack Endurance Test

Recent fuel cell stack endurance test experience is demonstrating the suitability of cell components identified under the Lewis technology program for use in the fuel cell stack for the Engineering Model System.

The fuel cell stack assembly employed in the RFCS study is shown in Figure 29. Significant cell components with the potential to extend operating life and reduce cell weight are: (1) the butyl bonded potassium titanate matrix, (2) the molded PPS cell edge frame, (3) the graphite electrolyte reservoir plate and (4) the photoetched substrate electrode. All of these cell components have successfully been incorporated into full-size cells and endurance tested.

The butyl rubber bonded potassium titanate matrix has been incorporated into Orbiter-type 0.508 ft^2 (472 cm^2) cells and endurance tested in two, multi-cell stacks. A photograph of the corrosion resistant matrix is shown on Figure 24.

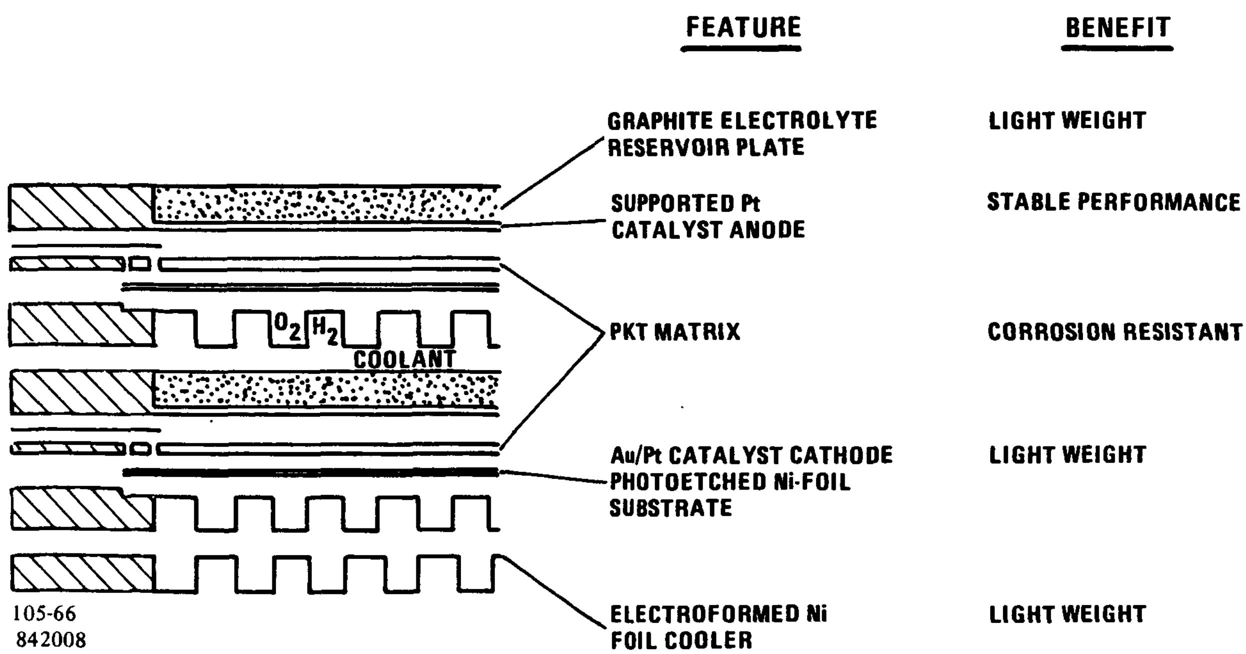

Figure 29. Fuel Cell Stack Assembly

The molded PPS cell edge frame shown on Figure 27 has been successfully incorporated into the cells of two full-size Navy stack endurance tests. The improved corrosion-resistant frame will be employed in future full-size stacks endurance tested under the Lewis program.

When the graphite electrolyte reservoir plate (ERP) is incorporated into the Orbiter production cell, replacing the heavy porous nickel ERP, the cell weight is reduced by 47 percent. Graphite ERP's have been successfully endurance tested in two full-size 0.508 ft^2 (472 cm^2) area multi-cell stacks under the Lewis program. A photograph of the graphite ERP is shown on Figure 25.

The photoetched nickel foil substrate electrode shown on Figure 30 was developed under the Lewis program. There have been many successful endurance tests of laboratory research cells employing this electrode configuration. The Navy four-cell stack endurance test shown on Figure 28 contains cells with photoetched substrate electrodes.

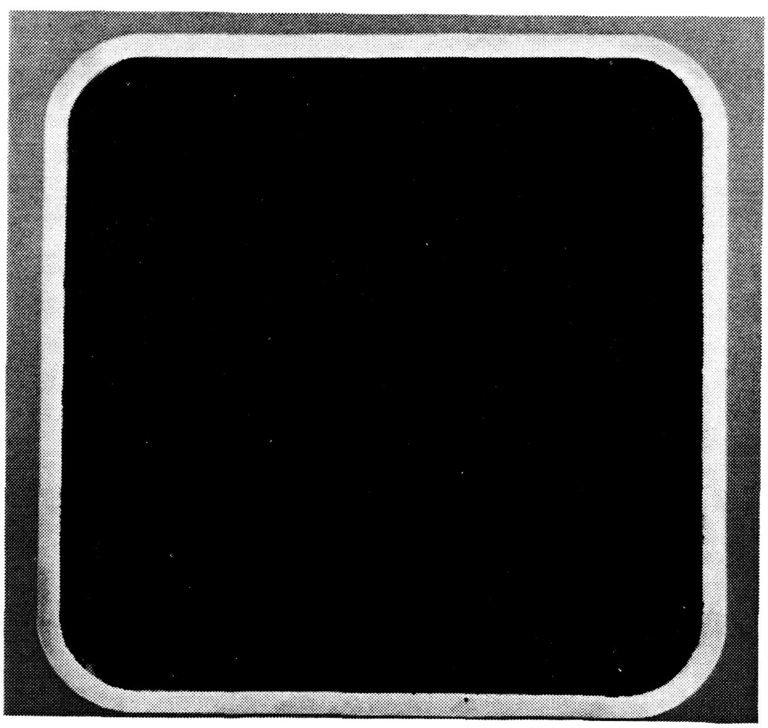

Figure 30.

Photoetched Substrate Electrode

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There are only two technical issues relating to the fuel cell and its application in a RFCS for space station. These issues are: (1) the long-life capability of the fuel cell stack and (2) the fuel cell stack tolerance to launch and space environment. In order to resolve these technical issues, the demonstration tests identified in Table V are recommended.

Table V. Recommended Fuel Cell Stack Demonstration Tests

- DEMONSTRATE LONG-LIFE CAPABILITY OF THE STATE-OF-THE-ART CELL STACK.
- DEMONSTRATE LONG-LIFE CAPABILITY OF THE ADVANCED CONFIGURATION CELL STACK
- DEMONSTRATE FUEL CELL STACK TOLERANCE TO LAUNCH AND SPACE ENVIRONMENT

The long-life endurance tests of fuel cell stacks to a cyclical load profile simulating RFC operation will demonstrate cell performance stability and stack structural integrity. The goal of these tests should be to demonstrate the endurance capability of a flight-weight cell configuration. The concern of stack tolerance to launch and space environment is focused upon the ability of the cell stack and lightweight graphite electrolyte reservoir plate to withstand the acceleration and vibration associated with launch.

B. Electrolyzer Cell

The weight, volume and performance characteristics for the electrolyzer cell were provided to United by NASA. The characteristics of the solid polymer electrolyte cell are presented in Reference 16. Reference 16 summarizes the characteristics of the alkaline water electrolysis cell. These references did not identify any fundamental cell area scale-up or operating life limitations.

The performance of the alkaline electrolysis cell is shown in Figure 31. The performance shown at 140°F (60°C) and 180°F (82.2°C) is valid for an operating pressure range from ambient to 550 psia (379.2 N/cm^2) at beginning of life.

Solid polymer electrolyte performance at 300 psia (206.8 N/cm^2) at a cell temperature of 140°F (60°C) and 180°F (82.2°C) is shown on Figure 32. Electrolysis cell performance data at high operating pressures was not identified in Reference 16. The performance level shown on Figure 32 is similar to the alkaline performance data presented on Figure 31. The solid polymer electrolyte performance is valid at the beginning of life.

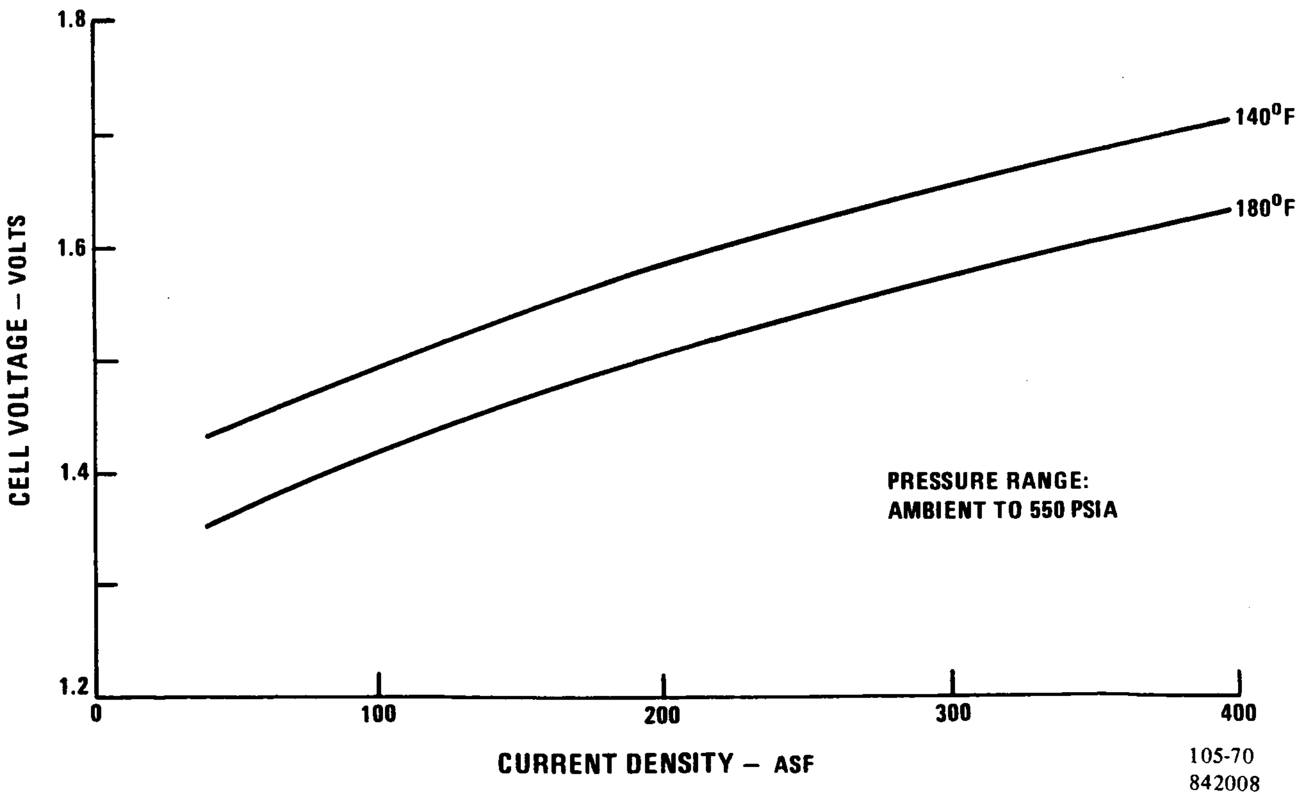

Figure 31. Alkaline Electrolysis Cell Performance

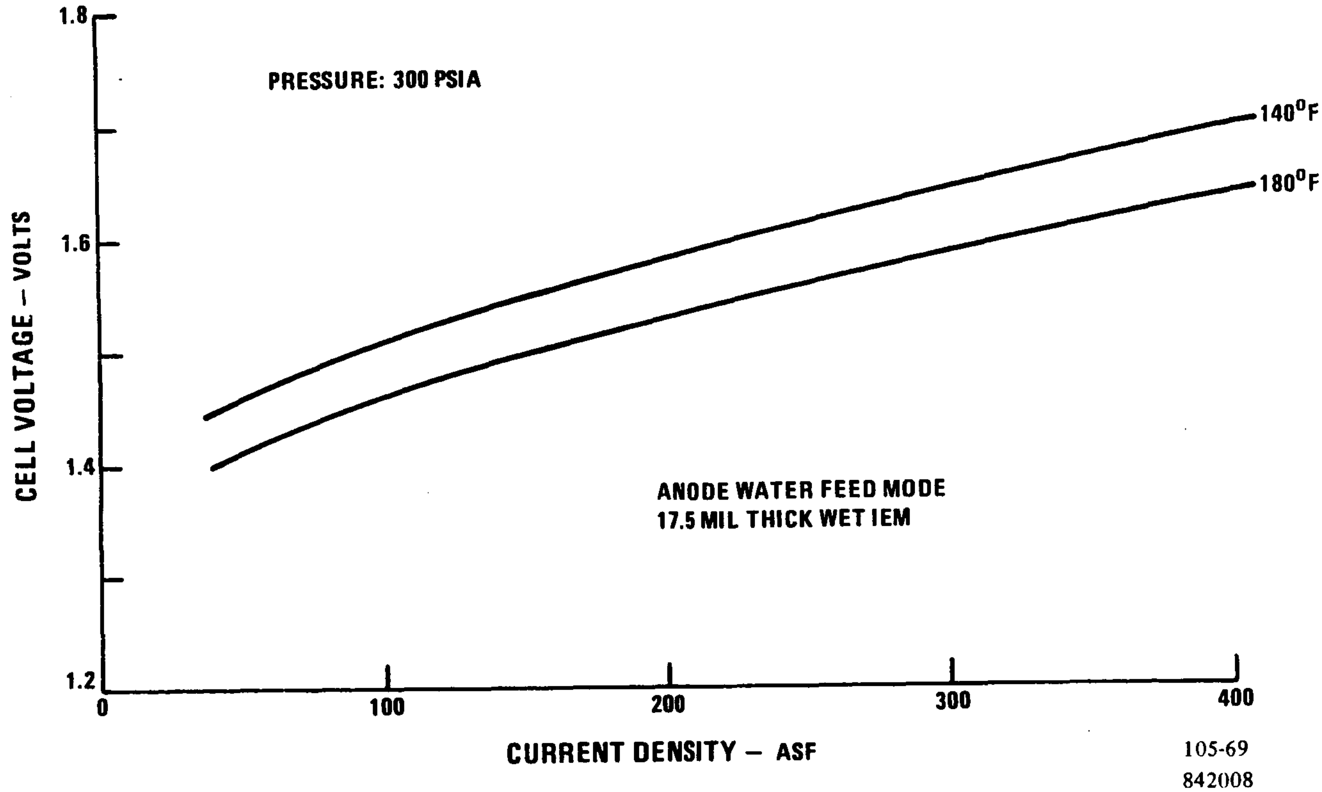

Figure 32. Solid Polymer Electrolyte Electrolysis Cell Performance

The status of the electrolysis cell development activities as pertaining to operating life is shown graphically on Figure 33. In small laboratory size cells both the alkaline and solid polymer electrolyte electrolyzer technologies are approaching or have met the 40,000-hour life goal. However, demonstration tests discussed in the literature of the long-life of full-size multi-cell stack electrolyzers has only demonstrated 25 percent of the life goal.

There are three technical issues relating to the electrolysis cell and the application in a RFCS for space station. These issues include: (1) manufacturing capability to scale-up from laboratory-size cells, (2) limited large-size alkaline electrolyzer test experience and (3) tolerance to the launch environment and space conditions. The issue relating to manufacturing capability to scale-up from lab-size cells is directed toward the alkaline electrolysis cell. For EMS and RFCS application, a five to ten times area increase must be demonstrated with the alkaline cell. Large-size

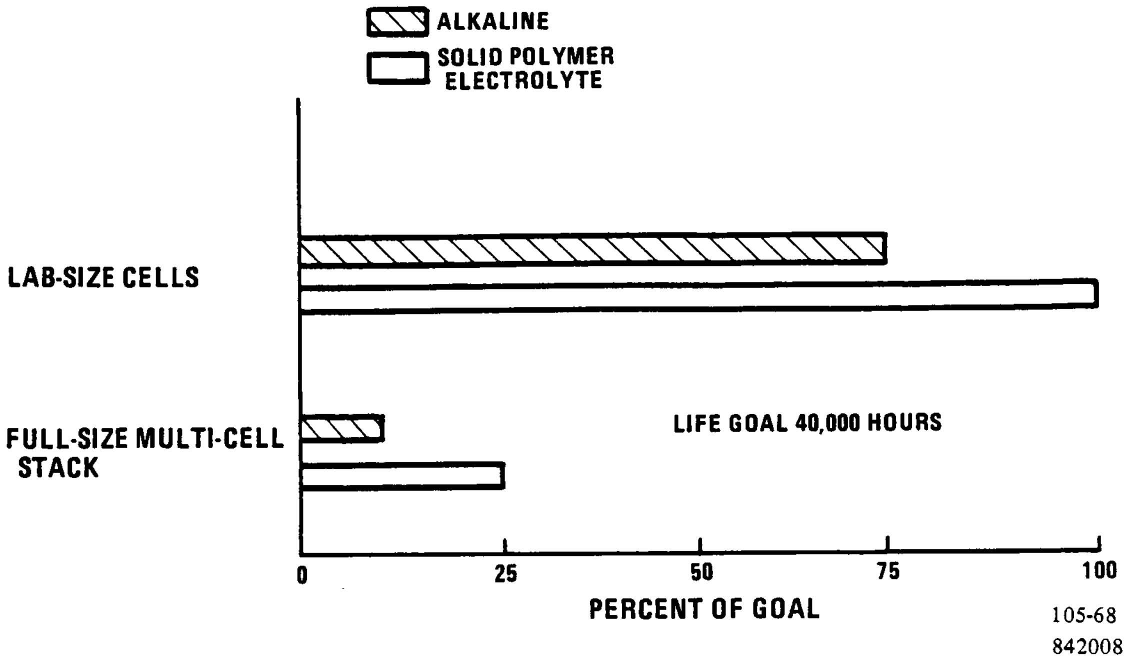

Figure 33. Electrolysis Cell Technology Status

solid polymer electrolyte cell stacks containing 100 cells have been fabricated and endurance tested under a Navy program. A demonstration test program conducted by the electrolyzer manufacturer including the recommended demonstration tests outlined in Table VI is an approach to resolve identified technical issues.

Table VI. Recommended Electrolysis Cell Stack Demonstration Tests

- ENDURANCE TEST FULL-SIZE ALKALINE ELECTROLYSIS CELL
- DEMONSTRATE LONG-LIFE ON FULL-SIZE ELECTROLYSIS CELL STACK
- DEMONSTRATE ELECTROLYSIS CELL STACK TOLERANCE TO LAUNCH AND SPACE ENVIRONMENT

A long-term endurance test of a full-size alkaline electrolysis cell at high pressure, 300 psia (206.8 N/cm²) or higher will demonstrate: (1) successful scale-up from laboratory-sized cells and (2) long-term performance stability. All endurance tests should be conducted on flight-weight cell configurations. Long-term endurance tests of full-size electrolysis cell stacks to a cyclical load profile simulating RFCS operation will demonstrate cell performance stability and stack structural integrity. In addition the capability of the electrolysis cell to operate on fuel cell product water will have to be demonstrated. The concern of electrolysis cell stack to launch and space environment is focused upon the ability of the stack to withstand the acceleration and vibration associated with launch.

C. Ancillary Components

The design approach for the ancillary components in the RFCS is to employ Orbiter fuel cell power plant experience with improvements in the components as required to extend operating life. A brief review of the Orbiter system was conducted to identify pacing technology items. The majority of the system components including the pressure regulator, valves, sensors, and coolant pump have an expected 40,000-hour operating life with the component improvements in process or identified under the Orbiter fuel cell program. This review identified only two ancillary components, the hydrogen pump and water pump, requiring development work under the EMS approach.

An Orbiter hydrogen pump, shown on Figure 34, employed in the six-cell stack cyclical endurance test completed 12,000-hours of operation without maintenance. The operating life of the hydrogen pump is a function of bearing design and lubrication approach. A shielded bearing is employed in all production hydrogen pumps. An improved sealed bearing which traps the lubricant in the bearing has been incorporated into the hydrogen pump employed in a four-cell stack endurance test being run under the Lewis program.

A water pump is required in the RFCS to transfer fuel cell product water to the electrolyzer. This pump operates intermittently filling a water storage tank in the electrolysis cell system and pressurizes the water to electrolyzer pressure. There is no comparable component in the Orbiter fuel cell power plant. However, United expects the water pump to have an operating life at least as good as the hydrogen pump. In selecting a cyclical water pump, a design would be identified with the potential for long-life.

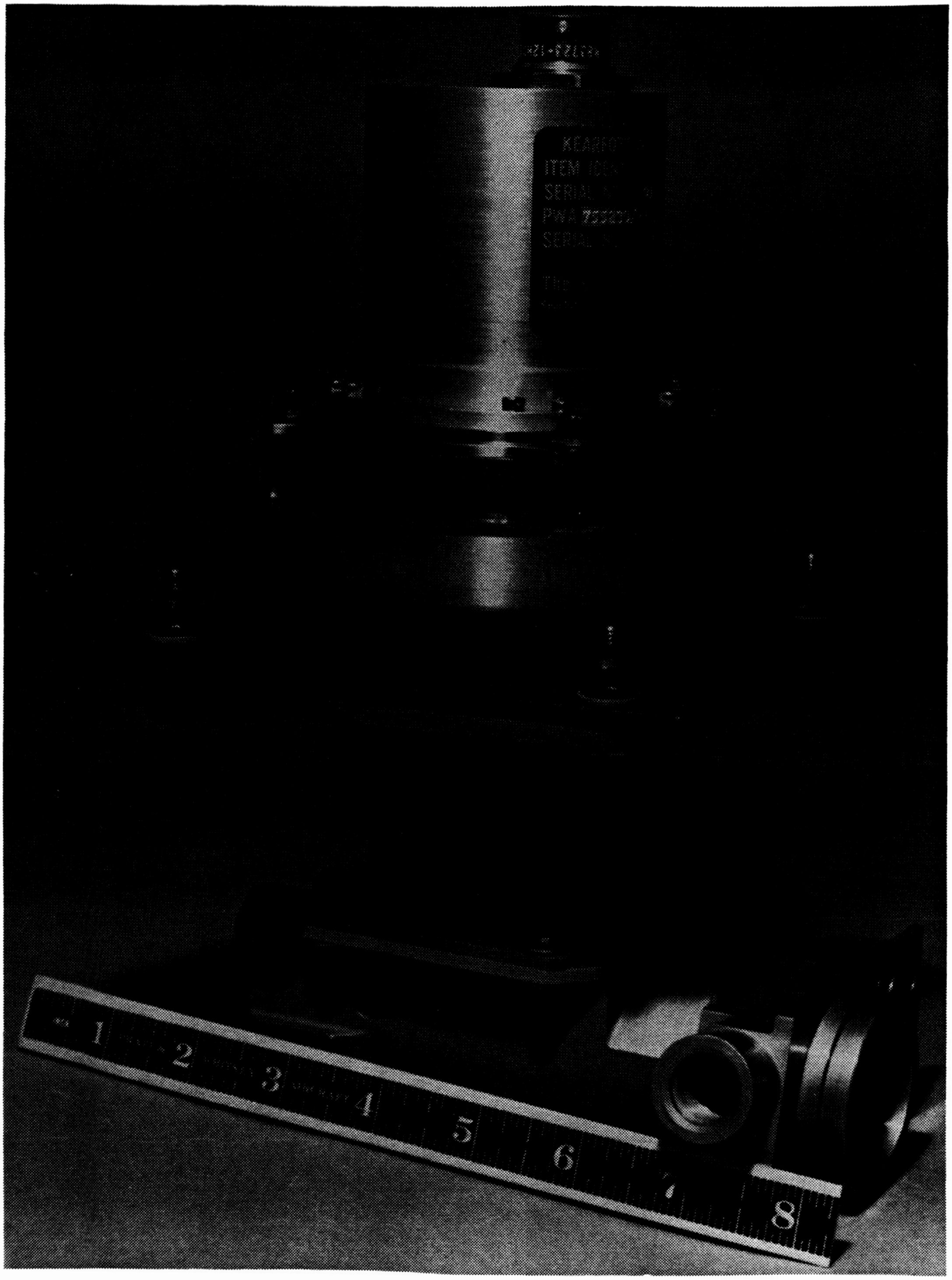

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Figure 34. Hydrogen Recirculation Pump

The technology status of the ancillary components is summarized in Figure 35.

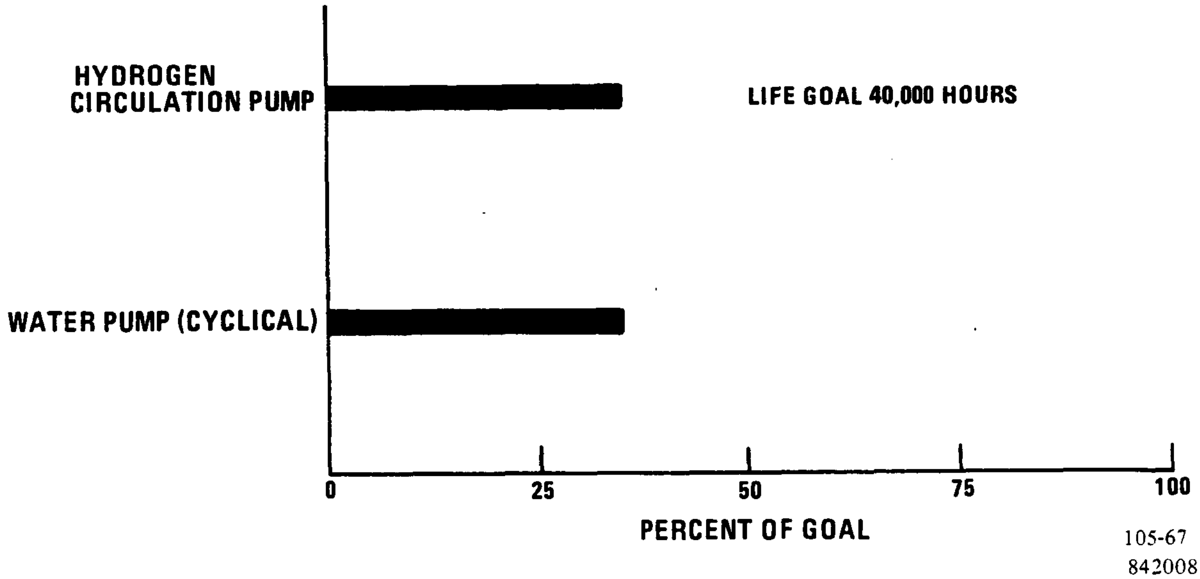

Figure 35. Ancillary Component Technology Status

Thus there are only two technical issues pertaining to the ancillary components in the RFCS. These are bearing and seal life of the hydrogen recirculation pump and water pump. The approach to improving the operating life of these components is to improve bearing lubrication and incorporate superior bearing seal designs. With these modifications a component operating life of 40,000-hour is attainable. Alternate bearing design concepts are also available including gas bearings for the hydrogen pump and a magnetic clutch for the water pump.

Three demonstration tests are required as identified in Table VII to verify the suitability of the improved ancillary components for use in the RFCS for space station.

Table VII. Recommended Ancillary Component Demonstration Tests

- DEMONSTRATE HYDROGEN PUMP LIFE
- DEMONSTRATE WATER PUMP LIFE
- COMPONENTS INTEGRATION

A 40,000-hour endurance test of the hydrogen and water pump should be conducted at anticipated RFCS operating conditions. Component integration tests of sub-systems including hydrogen and oxygen loops are required. These integration tests are important in order to verify the system design concept.

D. System Integration

System integration tests culminating in the fabrication and demonstration testing of an Engineering Model System (EMS) is necessary to verify the operational capability of RFCS design concept. These tests will demonstrate:

- System Integration
- Selected Control Approach
- Trouble-Free Operation
- Operation at Vehicle Voltage
- Operation at Design Power Density
- Operation to Orbital Cycle
- Efficiency
- Transient Power Capability

The physical configuration of the RFCS and system packaging flexibility will be demonstrated by the integration tests.

The system integration tests will also demonstrate alternate operating modes of the EMS. This test will demonstrate the ability of the system to operate on reactant and water supplied from an external source within the space station. The system integration test will demonstrate the capability to provide potable water and/or reactants to the space station. Emergency power capability can also be demonstrated.

The integration test will demonstrate the simplicity of system operation. The RFCS will be capable of automatic startup, autonomous operation and fail safe shutdown.

The EMS integration testing will also demonstrate the ease of maintaining the RFCS. The EMS and characteristics are presented in Section VI.

VI. ENGINEERING MODEL SYSTEM CHARACTERISTICS

An early demonstration and evaluation of a "prototype" regenerative fuel cell system to establish its applicability for the Space Station is the goal of the Engineering Model System (EMS) program. At this point in time, it is expected that the EMS configuration will be dictated by the availability of system components. It is expected that the larger coolant and hydrogen pumps required for the Space Station RFCS will not be available for the EMS. The use of Orbiter fuel cell power plant components (improved where applicable) will limit the EMS to a steady state maximum power of approximately 10 kW at a nominal cell temperature of 180°F(82.2°C). It should be pointed out that the selection of the operating conditions within the system are based on a preliminary thermodynamic analysis that might change as requirements for the powerplant are established and/or modified, such as, power turndown, voltage regulation, abort start capability, and coolant return temperature limitations.

The EMS is not expected to be a demonstration of a Space Station size power plant but would be designed with electrochemical cell components and ancillary components with the potential of long-life. The EMS is expected to provide verification of the operational capability of the RFCS. It is expected to be a trouble-free demonstration of the integration of the fuel cell and electrolyzer subsystems operating to an orbital cycle and load profile. Its physical configuration and packaging as well as the control approach will conform to the Space Station concept and will be valid verification.

The fuel cells and electrolysis cells will include the best technology available at the time the EMS is built. The cell sizes are expected to be the present configurations, 0.5-ft^2 active area fuel cell and if the alkaline electrolyzer is chosen, a 1.0-ft^2 active area electrolysis cell. Whether these cell sizes will be changed for the space station RFCS will depend on the final power plant requirements, such as, cost, power, voltage regulation, efficiency, or weight. With these cell sizes, the EMS can demonstrate operation at the space station bus voltage, the RFCS power density (watts/ft^2 of cell area) and the expected system efficiency.

In addition to demonstrating performance, configuration and integration as described above, the EMS will be able to demonstrate the alternate operating modes associated with integration of the RFCS into other space station systems. It will operate in the power producing mode with reactants from external tankage and produce hydrogen and oxygen for consumption outside from water supplied from an external source.

The EMS will include the RFCS type of controller and will be able to demonstrate the simplicity of system operation with automatic startup and autonomous operation.

A. System Schematic

The fluid schematic of the EMS is shown in Figure 36. The schematic is identical to that of the RFCS presented in Section III. Component designations have been added along with sensor designations and station numbers. The configuration of the integration interfaces have not been defined in this study.

B. Physical Configuration

A packaging concept of the EMS is shown in Figure 37.

C. EMS Characteristics

1. Module

The characteristics of the EMS are shown in Tables VIII, IX and X. These are based on the steady state design point conditions of the fuel cell and electrolyzer shown in Tables XI and XII. The temperature, pressure and flow rates throughout the system are shown in Tables XIII for the charge phase and XIV for the discharge phase. The station numbers on Tables XIII and XIV correspond to those on the EMS schematic shown in Figure 36.

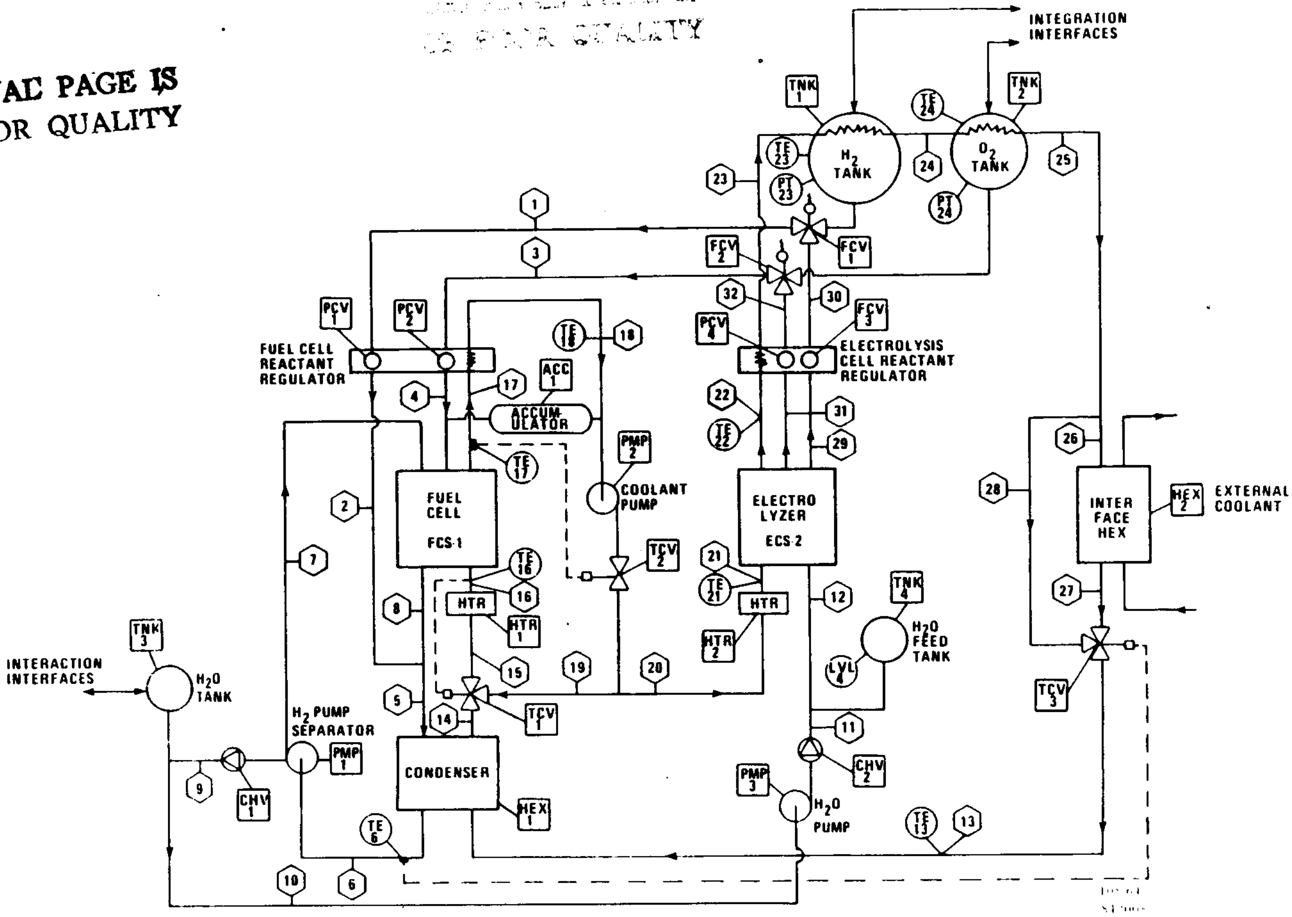

Figure 36. EMS System Schematic

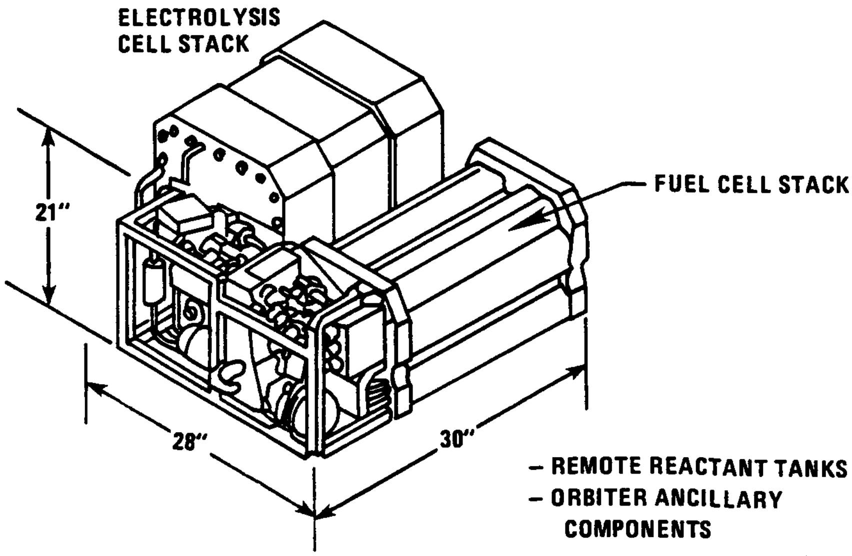

Figure 37. 10-kW EMS

105-65
841708

TABLE VIII. EMS CHARACTERISTICS

Module Rating	10kW
Orbital Cycle	
Light Side	58.8 Minutes
Dark Side	35.7 Minutes
Fuel Cell Output	
Voltage	101 Volts
Current	101 Amps
Electrolyzer Input*	
Voltage	50 Volts
Current	215 Amps

*Based on NASA Data

TABLE IX. EMS CHARACTERISTICS - EFFICIENCY

Fuel Cell	69.4 Percent
Electrolysis*	82.6
Fuel Cell Unit	68.3
Electrolyzer Unit	81.1
Module	55.4

*Based on NASA Data

TABLE X. EMS CHARACTERISTICS - ESTIMATED WEIGHT

Fuel Cell Power Section	145 Pounds
Electrolyzer Power Section*	203
Accessory Section	84
Tanks	14
Reactants	5
Controller	10
Total	461 (12.91 $\frac{\text{Watt-hrs}}{\text{lb}}$)

*Based on NASA data

TABLE XI. EMS CHARACTERISTICS - FUEL CELL OPERATION

Gross Power	10170 Watts
Parasite Power	165 Watts
Number of Cells	116
Cell Area	0.508 Ft^2
Current Density	199 $Amps/Ft^2$
Cell Voltage	.869 Volt
Cell Inlet Temperature	180°F
Operating Pressure	60 Psia

TABLE XII. EMS CHARACTERISTICS - ELECTROLYZER OPERATION*

Gross Power	10799 Watts
Parasite Power	168 Watts
Number of Cells	33
Cell Area	1.0 Ft^2
Current Density	215 Amps/Ft^2
Cell Voltage	1.515 Volts
Cell Inlet Temperature	180°F
Operating Pressure	300 Psia

*Based on NASA data

TABLE XIII. EMS DESIGN TABLE

****** CHARGE PHASE ******

LOCATION NO.	NAME	TEMP DEGF	PRESS PSIA	MOLE FRACTIONS H2	H2O	O2	N2	A	COOLANT	TOTAL FLOWS MOLES/HR	LBS/HR
1	H2 TANK EXIT	180.	300.0	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
2	FC H2 FEED	180.	61.6	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
3	O2 TANK OUT	181.	300.0	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
4	FC O2 FEED	181.	61.6	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
5	COND H2 IN	179.	61.6	0.880	0.120	0.0	0.0	0.0	0.0	5.7920	22.819
6	COND H2 OUT	179.	61.6	0.880	0.120	0.0	0.0	0.0	0.0	5.7920	22.819
7	FC H2 IN	179.	61.7	0.880	0.120	0.0	0.0	0.0	0.0	5.7920	22.819
8	FC H2 OUT	179.	61.6	0.880	0.120	0.0	0.0	0.0	0.0	5.7920	22.819
9	FC H2O OUT	179.	61.6	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
10	H2O PUMP IN	179.	61.6	0.0	1.000	0.0	0.0	0.0	0.0	.35479	6.3919
11	H2O PUMP OUT	179.	300.0	0.0	1.000	0.0	0.0	0.0	0.0	.35479	6.3919
12	EC H2O IN	179.	300.0	0.0	1.000	0.0	0.0	0.0	0.0	.29994	5.4038
13	FC UNIT CLT IN	180.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
14	COND CLT OUT	180.	61.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
15	HTR-1 CLT IN	180.	61.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
16	FC STK CLT IN	180.	61.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
17	FC STK CLT OUT	180.	60.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
18	FC CLT PUMP IN	180.	60.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
19	FC STK CLT B/P	179.	63.7	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
20	HTR-2 CLT IN	179.	63.7	0.0	0.0	0.0	0.0	0.0	1.000	2.4074	1564.8
21	EC STK CLT IN	179.	63.7	0.0	0.0	0.0	0.0	0.0	1.000	2.4074	1564.8
22	EC STK CLT OUT	180.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4074	1564.8
23	H2 TANK CLT IN	180.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4074	1564.8
24	O2 TANK CLT IN	180.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4074	1564.8
25	O2 TANK CLT OUT	181.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4074	1564.8
26	HEX-2 HOT IN	181.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4072	1564.7
27	HEX-2 HOT OUT	180.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	2.4072	1564.7
28	HEX-2 B/P	181.	62.6	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
29	EC H2 OUT	180.	300.0	0.982	0.018	0.0	0.0	0.0	0.0	.29740	.68538
30	H2 TANK IN	185.	300.0	0.982	0.018	0.0	0.0	0.0	0.0	.29740	.68538
31	EC O2 OUT	180.	300.0	0.0	0.018	0.982	0.0	0.0	0.0	.14870	4.7209
32	O2 TANK IN	185.	300.0	0.0	0.018	0.982	0.0	0.0	0.0	.14870	4.7209

TABLE XIV. EMS DESIGN TABLE

****** DISCHARGE PHASE ******

LOCATION NO.	NAME	TEMP DEGF	PRESS PSIA	MOLE FRACTIONS H2	H2O	O2	N2	A	COOLANT	TOTAL FLOWS MOLES/HR	LBS/HR
1	H2 TANK EXIT	207.	300.0	0.992	0.008	0.0	0.0	0.0	0.0	.48470	1.0399
2	FC H2 FEED	180.	60.5	0.992	0.008	0.0	0.0	0.0	0.0	.48470	1.0399
3	O2 TANK OUT	206.	300.0	0.0	0.008	0.992	0.0	0.0	0.0	.24235	7.7278
4	FC O2 FEED	180.	60.5	0.0	0.008	0.992	0.0	0.0	0.0	.24235	7.7278
5	COND H2 IN	208.	60.5	0.862	0.138	0.0	0.0	0.0	0.0	6.4061	27.012
6	COND H2 OUT	153.	60.4	0.933	0.067	0.0	0.0	0.0	0.0	5.9190	18.236
7	FC H2 IN	153.	60.7	0.933	0.067	0.0	0.0	0.0	0.0	5.9194	18.244
8	FC H2 OUT	211.	60.5	0.852	0.148	0.0	0.0	0.0	0.0	5.9214	25.972
9	FC H2O OUT	153.	60.4	0.0	1.000	0.0	0.0	0.0	0.0	.48697	8.7732
10	H2O PUMP IN	153.	60.4	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
11	H2O PUMP OUT	153.	300.0	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
12	EC H2O IN	153.	300.0	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
13	FC UNIT CLT IN	139.	61.5	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
14	COND CLT OUT	173.	60.5	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
15	HTR-1 CLT IN	180.	60.5	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
16	FC STK CLT IN	180.	60.5	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
17	FC STK CLT OUT	210.	59.5	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
18	FC CLT PUMP IN	210.	59.5	0.0	0.0	0.0	0.0	0.0	1.000	2.4077	1565.0
19	FC STK CLT B/P	210.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	.46192	300.25
20	HTR-2 CLT IN	210.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
21	EC STK CLT IN	209.	62.6	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
22	EC STK CLT OUT	209.	61.5	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
23	H2 TANK CLT IN	208.	61.5	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
24	O2 TANK CLT IN	207.	61.5	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
25	O2 TANK CLT OUT	206.	61.5	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
26	HEX-2 HOT IN	206.	61.5	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
27	HEX-2 HOT OUT	139.	61.5	0.0	0.0	0.0	0.0	0.0	1.000	1.9458	1264.7
28	HEX-2 B/P	206.	61.5	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
29	EC H2 OUT	209.	300.0	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
30	H2 TANK IN	209.	300.0	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
31	EC O2 OUT	209.	300.0	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0
32	O2 TANK IN	209.	300.0	0.0	0.0	0.0	0.0	0.0	0.0	.0	.0

The electrolyzer input voltage is based on the selection of 1.515 volt/cell electrolysis cell operating point and 1.0-ft^2 active area cell. This selection along with the fuel cell operating point that is dictated by its power output and voltage requirements results in the 55.4% system efficiency shown in Table IX. Selection of higher electrolysis cell voltages will result in lower system efficiency. Selection of lower cell voltages will not significantly improve the system efficiency. At voltages below the thermal neutral point (approximately 1.48 volts/cell) electric heaters are required to provide the endothermic heat of reaction in the electrolysis cell. The electrical energy required by these heaters as shown on Figure 38 completely offsets the improvement in cell efficiency at the lower voltage. The uncertainty in heat loss (and therefore heater operation) associated with EMS operation at sea level prompted the selection of the voltage above the thermal neutral point.

The energy density of the system shown on Table X is less than that of the optimized module presented in Figure 10 because the EMS is to be built with the cell sizes that are presently available instead of optimized cell sizes.

2. Fuel Cell

The fuel cell performance used to establish the design point is the conservative equivalent of the 180°F (82.2°C) space station RFCS fuel cell performance after 40,000 hours of operation (discussed in Section V). The number of cells in the fuel cell stack was established on the basis of the minimum output of 100 volts after 40,000-hours of operation. As stated above, this voltage, the power required, and the cell size (0.5-ft^2) define the fuel cell operating point of 199 amps/ft^2 (214 mA/cm^2).

3. Electrolyzer

The electrolysis cell performance used to establish the design point is the 180°F (82.2°C) cell performance discussed in Section V. As described above, the design operating point was selected to result in a near maximum system efficiency. For purposes of this study the alkaline electrolyzer was assumed. Similar performance and weight would be expected for an SPE electrolyzer.

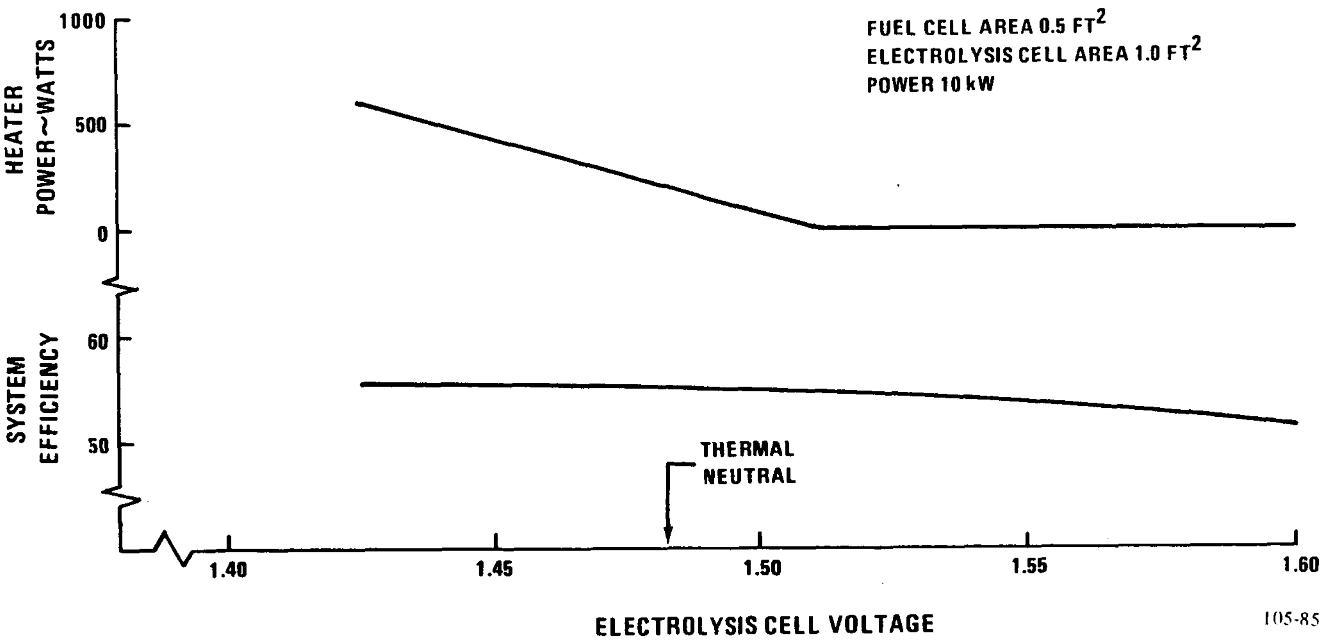

Figure 38. RFCS Module Heater Requirements

D. System Operation and Control Logic

This section is a preliminary description of the control logic and operation of the Space Station RFCS. The EMS will be functionally identical to the RFCS.

1. Operating Modes

It was a major premise of system design that each RFCS module should operate completely automatically. In order to accomplish that aim, three modes of operation were identified:

<u>Energy Storage</u> - This is the normal, "on-orbit" mode of operation in which the RFCS operates a cyclically to store energy and then produce power.

Power Only - This is a mode of operation in which only the fuel cell portion of the RFCS is used to produce power from externally supplied reactants. This might occur during the construction of the Space Station or during emergency, "safe-haven" operation.

Excess Reactants Mode - This is a mode of operation in which the RFCS is used to produce extra reactants for use in the life support and/or ancillary propulsion system. An external water supply is required.

In addition, there were four operating phases defined which apply to each operating mode. These are as follows:

Startup
Standby
Run
Shutdown

Each phase represents a unique set of control requirements which are discussed below. The discussion focuses on the Energy Storage mode. The operational variations that apply to the other two modes are then discussed.

ENERGY STORAGE MODE

In the Energy Storage mode, each operating phase is divided into two periods depending on solar exposure:

Charge period during solar exposure
Discharge period during solar eclipse

Because in space, the RFCS must discharge (supply power) during the solar eclipse and charge (receive power) during periods of solar exposure, it is possible to regulate these cyclic periods based on solar array voltage - switching to the charge period when the solar array supply voltage reaches a predetermined level and switching back to the discharge period when that voltage drops below a predetermined level. For the EMS, this control may be simulated by varying the supply voltage with a timer. Such a cyclic period control has been assumed for the following discussion.

Startup - The purpose of the startup phase of operating is to bring the RFCS module to operating temperature as rapidly as possible. During the period of solar exposure, the module is powered from the solar array and may charge the reactant tanks if needed. During the period of solar eclipse, the module can "boot-strap" itself with the fuel cell providing all the power needed to bring the module to operating condition. The details of this phase of operation are described below.

During the solar exposure portion of the cycle, all power is supplied by the solar array, and the RFCS operates in the charge period. When the start is initiated pumps PMP-1, PMP-2 and PMP-3 are energized (see Figure 36). With full coolant flow established, (TCV-2 fully open) both heaters, HTR-1 and HTR-2, are energized and power is supplied to the electrolysis cell stack. Coolant recirculation around the fuel cell stack is minimized (TCV-1 in minimum by-pass position) and the interface heat exchanger is fully by-passed. (TCV-3 in full by-pass position). Heatup continues until the electrolysis cell stack exit temperature, as indicated by TE-22, reaches 180°F(82.2°C). This event signals "start complete" and all controls reset to normal operating schedules.

If, during a light-side start, pressure in the reactant storage tanks indicates that a fully charged state has been achieved, power to the electrolysis cell is terminated but the heatup continues as before.

During the solar eclipse period of the cycle all power for the start is supplied by the fuel cell. A start during this period may not be initiated if there is insufficient stored reactant gas, that is, system is not adequately charged. The minimum reactant pressure for a start to be initiated as indicated by either PT-23 or PT-24, must be TBD. When the start is initiated, the reactant supply valves are opened. All pumps (PMP-1, PMP-2 and PMP-3) and heaters (HTR-1 and HTR-2) are then powered from the fuel cell as the system heats up. No external load is applied during the start. Coolant recirculation around the fuel cell stack is maximized (TCV-1 in maximum by-pass position) and the interface heat exchanger is fully by-passed (TCV-3 in full by-pass position) until condenser exit temperature control is required. The fuel cell heater, HTR-1, remains on until start-complete. The electrolysis cell heater follows the normal control schedule with coolant exit temperature as indicated by TE-22. When the fuel cell stack coolant exit temperature, as indicated by TE-17, reaches 180°F (82.2°C), the start is complete and all controls are reset to normal generating schedules.

Standby Phase - Standby is a phase of operation in which the RFCS module is at temperature but is not required to produce any net power. A module might hold in the standby phase for some time after a completed start, during trouble shooting, or before being shutdown. Standby might also be used for load management, that is, reduce the number of power producing modules on line during low load periods.

Standby During Charge Period - Because the only load on the RFCS module while in the standby phase is the parasite power of the heater, pumps and controls in the module itself several charging cycles may be by-passed before the module becomes sufficiently discharged to require recharging. During standby, the module is not charged until the reactant tank pressures fall below TBD psia. Thus, ordinarily, the electrolysis cell unit does not operate during each period of solar exposure. All pumps are on, and heaters operate as required to maintain the respective stack exit temperature at 180°F (82.2°C). The fuel cell stack coolant inlet valve, TCV-1, modulates the stack coolant by-pass flow to maintain stack inlet temperature at 180°F (82.2°C). The main coolant throttle valve, TCV-2, is not modulated and remains full open. Finally, the condenser exit temperature control valve modulates to maintain TCE at TBD°F.

Standby During Discharge Period - During the discharge period the fuel cell unit in standby phase supplies the parasite power for the module and consumes stored reactants in so doing. The electrolysis cell unit is off. All heaters and valves continue to control as previously described for the standby phase.

Run Phase - Run is the normal "on load" phase of operation for the RFCS module.

Run During Charge Period - During solar exposure, the electrolysis cell receives power from the solar array, electrolyzes water and produces reactant gases at pressure. The fuel cell is off. This is the "charge period" of the RFCS cycle.

After full power is applied to the electrolysis cell unit, the electrolysis function proceeds until the vehicle passes into solar eclipse or until the reactant tank pressure reaches TBD psia (indicating full charge) whichever occurs first. This latter may occur if the load on the RFCS during solar eclipse is below rated capacity. All pumps are on with the feedwater pump, PMP-3 running intermittently in response to the quantity sensor LVL-4, in the water feed tank, TNK-4. The temperature control valves are controlling except for the fuel cell coolant exit temperature control valve, TCV-2, which is fixed in a full open position during this phase in order to provide full coolant flow to the electrolysis cell, and the condenser exit temperature control valve (TCV-3) which allows the temperature to increase to TBD°F to prevent condensation in the H_2 recirculation loop.

Run During Discharge Period - During solar eclipse, the fuel cell supplies load to the vehicle while using reactants stored previously from the electrolysis of water, and produces water for future electrolysis. The electrolysis cell is off. This is the "discharge period" of the RFCS cycle.

After load is applied to the fuel cell unit, power is available until the vehicle passes into solar exposure, or until the reactant tank pressure falls to TBD psia (indicating full discharge) whichever occurs first. The latter might occur if a greater than rated load was imposed on the RFCS or the charging cycle was, for some reason, incomplete. All controls function as described for the charge period except the fuel cell coolant exit temperature control valve, TCV-2, which operates to maintain fuel cell stack exit temperature of TBD°F, and the H_2 condenser exit temperature control valve, TCV-3, which operates to maintain that temperature at TBD°F.

Shutdown Phase - Shutdown is a condition of the RFCS module when no power is produced, no electrolysis takes place and the module is not at operating temperature.

The RFCS module is essentially off except for the provisions required to prevent water freezing. This is accomplished by maintaining coolant flow (PMP-2 on) and operating the heaters to maintain the respective cell stack coolant exit temperatures of, ~ 50°F (10°C). The parasite power required for this temperature maintenance function is supplied from an external source.

POWER ONLY MODE

Unlike the Energy Storage mode, the Power Only mode is independent of the solar exposure cycle because reactants are supplied from an external source. Interfaces for this gas supply are through the reactant storage tanks.

In the Power Only mode, all operational phases are the same as described for the Energy Storage mode operating during the discharge period (solar eclipse). Excess water produced during the operation of the fuel cell unit must be stored or discharged from the RFCS. The equipment (valves, etc.) and controls required for the external reactant supply are not part of the RFCS.

EXCESS REACTANT MODE

The Reactant only mode, like the Energy Storage mode, is dependent on the solar exposure cycle because solar energy is necessary to operate the electrolysis cell unit even though the extra water required is supplied on demand from an external source to the RFCS water storage tank.

In the Excess Reactant mode, all operational phases are as described for the charge period of the Energy Storage mode. External reactant storage tanks from the RFCS are required. Gas is stored on a cyclic basis, but may be withdrawn on any required schedule so long as the storage tanks are not exhausted below the prescribed minimum operating pressure.

2. Component Requirements

Preliminary component requirements are presented in Appendix B. These requirements are included for format only and are not complete since all the operating modes of the EMS could not be evaluated. The requirements that are presented are for the valves and the sensors. Also included are the control logic (status) and control schedules.

VII. ENGINEERING MODEL SYSTEM DEVELOPMENT PLAN

A plan for the design, development, and delivery of the 10-kW Engineering Model System (EMS) RFCS is shown in Figure 39. The EMS is ready for delivery to NASA approximately two and one half years into the program.

As shown on Figure 39 there are seven major activities required for the development of an EMS. This plan is predicated on the existence of two technology development programs at United for fuel cell, and ancillary improvement. A components technology program with Johnson Space Center of NASA would provide an early screening and evaluation of improved ancillary components for the RFCS. The Fuel Cell Technology Advancement Program sponsored by Lewis Research Center of NASA would identify and evaluate the long-life, lightweight fuel cell configuration desired for the Space Station RFCS.

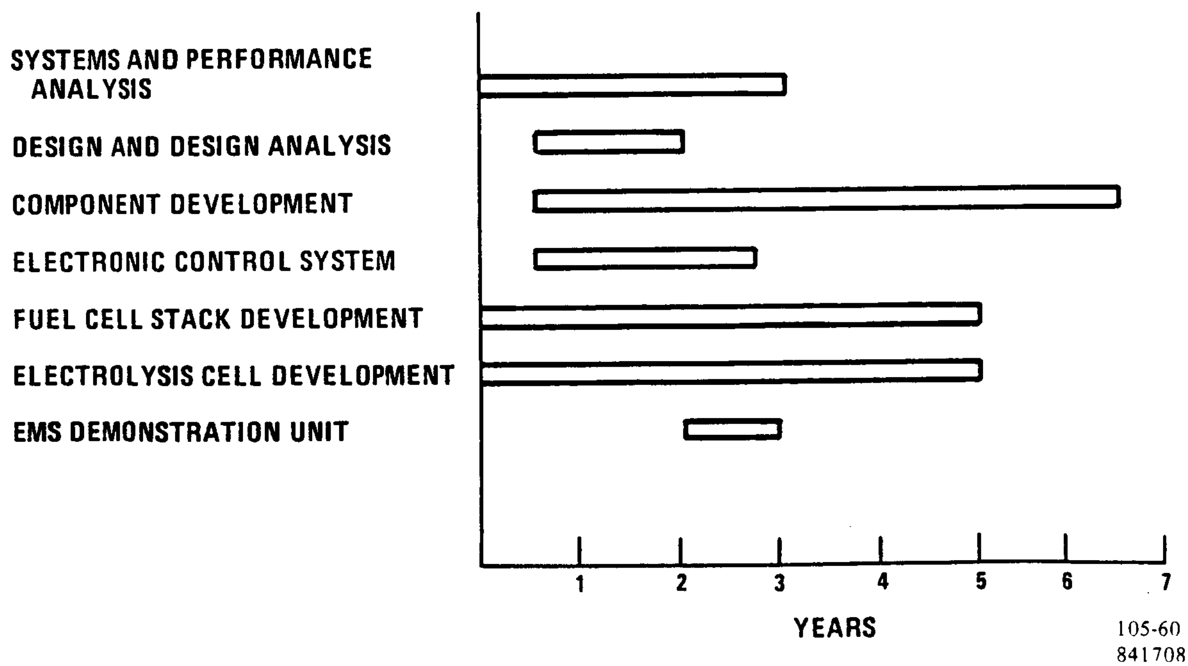

Figure 39. EMS Program Development Schedule

Systems and Performance Analysis

There are two objectives of the work planned under this activity. The first under Systems Analysis is to optimize the Regenerative Fuel Cell System Design for Space Station. The second under Performance Analysis is to evaluate development program test results, to identify any component improvements required to meet the RFCS program long-life goal.

System Analysis

The impact upon Regenerative Fuel Cell System of system efficiency, power level, system weight and volume will be a major factor in the design of the RFCS. The design work, therefore must be a joint effort by the RFCS designer and the Space Station designer. The primary factors to be considered are identified in Table XV.

TABLE XV. RFCS DESIGN FACTORS

- Reliability and Redundancy
- Power Profile
- Voltage Regulation Requirements
- System Efficiency
- Weight
- Volume
- Alternate System Operating Modes
- Operational Simplicity
- Maintenance
- Physical Configuration

The work under the activity will be to define system design guidelines and evaluate alternate RFCS designs. The output of this effort is a system design table which includes a mass and energy balance of the system showing temperatures, pressures and flows at significant points within the system. In addition the design table provides system performance predictions and permits the system analyst to prepare component design requirements.

The suitability of modified Orbiter fuel cell power plant ancillary components for use in the planned early demonstration test of an Engineering Model System (EMS) will be determined. An EMS design table employing these modified ancillary components will be prepared.

Performance Analysis

The effort under this activity provides continual evaluation of development program testing to identify any required component improvements to meet the program long-life goal.

Test plans for the experimental units to be evaluated under the component development, electronic control system and fuel cell stack development activities will be prepared. As part of the test plan, test data requirements will be identified and instrumentation requirements will be specified.

Periodic reviews of the test data from all experimental unit testing including the scheduled checkout testing of the EMS will be conducted. Upon completion of the data review, a performance summary report will be prepared.

Design and Design Analysis

This effort includes the preparation of a detailed system design supported by design analysis and experimental verification of critical design assumptions. The major output from this activity will be the preparation of detailed design drawings for the EMS and the RFCS for the Space Station application. These drawings will be required for the development and procurement of system ancillary components, and for the fabrication and final assembly of the Regenerative Fuel Cell System.

Design analysis support of the component development activities will be provided. Detailed calculations to identify system heat losses and loop pressure losses will be conducted. Design verification of vendor supplied reactant and water storage tanks for the EMS will be conducted.

A detailed analysis of the Regenerative Fuel Cell System and subsystem components will be conducted to insure the design which is tolerant to the launch and space environment. This study will determine the impact of launch acceleration and vibration upon the system. In addition the affect of operating in a space vacuum will be evaluated.

Component Development

This effort will result in the preparation of component designs and purchase specifications based upon the component design requirements generated under the systems analysis activity. An improved "Orbiter-type" hydrogen recirculation pump and a long-life cyclical water pump will be evaluated. The component development schedule is presented in Figure 40.

The major activities under the effort will be the test evaluation of an improved hydrogen pump, water transfer pump and qualification testing of purchased components for the EMS.

The approach to the development of the hydrogen pump, will focus upon improving the existing pump as discussed in Section V, C. The approach to the water transfer pump will be to survey supplier designs and select the best configuration for long-life. A long-term endurance test of both the hydrogen pump and water transfer pump will be conducted.

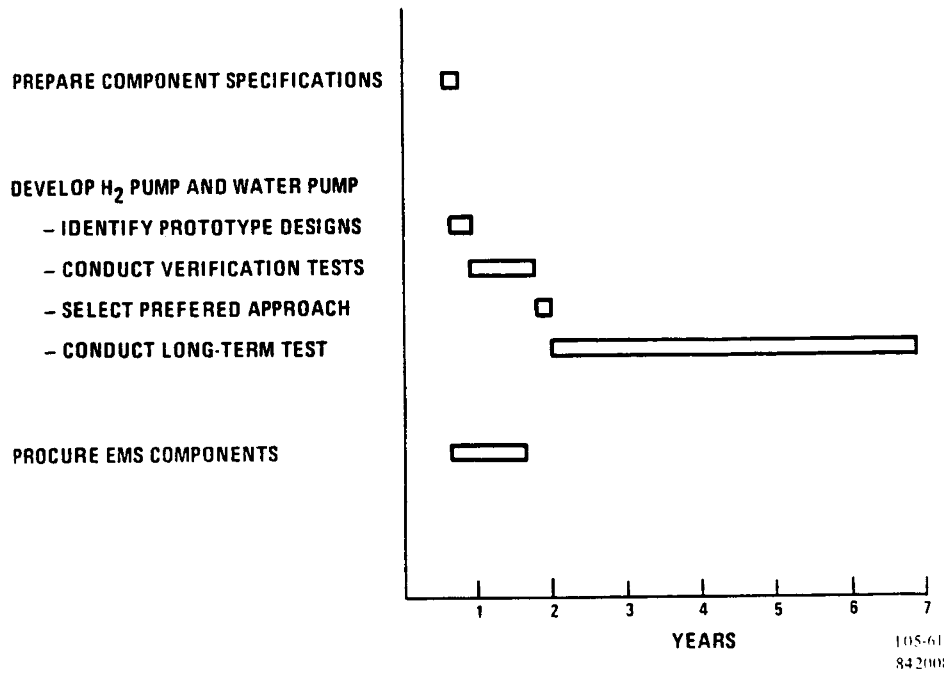

Figure 40. EMS Program Component Development Schedule

All delivery ancillary components will be tested prior to installation into the EMS. An improved Orbiter hydrogen pump and a long-life cyclical water pump will be available for use in the EMS. The long-life demonstration test of these two ancillary components starts in the second year of the program.

Electronic Control System

The Regenerative Fuel Cell System will incorporate an Electronic Control System (ECS) which will control the overall operation of the RFCS. The control concept will be to provide automatic startup from a Space Station initiated signal, autonomous operation and a fail-safe shutdown upon receipt of a Space Station generated signal. The ECS will be capable of transmitting performance information for crew monitoring of RFCS operation and alarm signals when specified control parameters are exceeded.

This effort will consist of defining ECS design requirements, preparing a purchase specification and canvassing potential suppliers. Upon selection of a supplier, a pre-prototype control system will be designed and fabricated. Evaluation of the pre-prototype unit at United will provide test data to help identify any modifications required in the ECS control logic. A prototype ECS unit will be constructed for the EMS. This ECS will be tested by the supplier prior to installation into the EMS.

Fuel Cell Stack Development

The fuel cell stack for the EMS will be constructed with cells incorporating long-life, lightweight components identified under the NASA-Lewis sponsored fuel cell technology advancement program. Under this technology program, advanced fuel cells incorporating lightweight cooler assemblies and graphite electrolyte reservoir plates, stable long-life cell edge frames and bonded potassium titanate matrices are being evaluated. Based upon these screening evaluation tests, a cell configuration(s) for the EMS stack will be selected. The long-life potential of the improved alkaline fuel cell will be demonstrated under the Lewis technology program.

The EMS program fuel cell stack development schedule is presented on Figure 41. The significant cell stack tests scheduled under the fuel cell technology advancement program are shown in order to identify milestones for the definition of EMS stack cell configuration.

The EMS fuel cell stack development effort will include performance and endurance testing of production development multi-cell stacks and a full-size EMS prototype stack. The final activity will be to construct and checkout test a full-size fuel cell stack for the EMS.

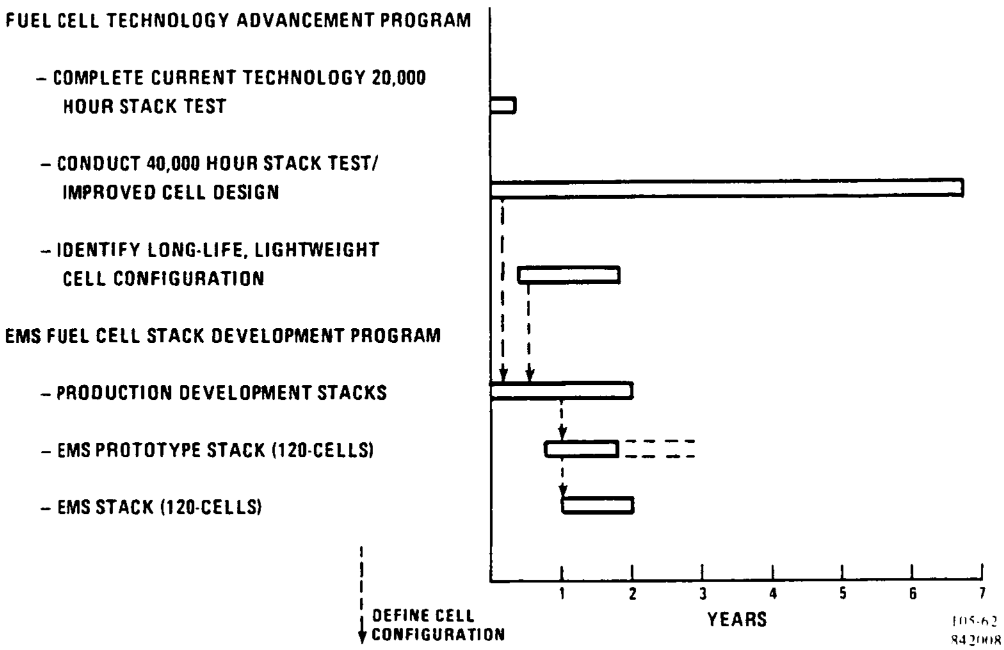

Figure 41. EMS Program Fuel Cell Stack Development Schedule

The purpose of the production development stacks is to evaluate the cell performance and endurance reproducibility of production cells. Cell manufacturing techniques and stack assembly procedures will have to be developed for the advanced cell configuration to be used in the EMS program. In addition, a large quantity of cells will be needed, requiring that cell production capability be increased, which would be accomplished by scaling-up present small lot cell manufacturing techniques.

Prior to the fabrication and checkout test of the EMS stack, a prototype EMS stack will be constructed and endurance tested. The purpose of the prototype stack will be to verify stack assembly methods and integrity and generate fuel cell endurance data on a full-size EMS stack.

Electrolyzer Cell Stack Development

The Regenerative Fuel Cell System design incorporates an alkaline electrolyte fuel cell and will be compatible with a water electrolyzer based upon either alkaline electrolyte or solid polymer electrolyte technology.

The initial effort under this activity will focus upon preparation of an electrolyzer stack purchase specification and surveying potential suppliers.

The electrolysis cell stack development program will be conducted by the supplier with project coordination provided by United. The electrolyzer program is anticipated to follow a similar development approach as outlined under fuel cell stack development. A prototype electrolysis cell stack will be constructed and endurance tested to demonstrate stack structural integrity and long-term performance stability.

An EMS electrolysis cell stack will be fabricated and tested by the supplier to an acceptance test procedure identified in the purchase specification. Upon completing the acceptance test, the stack will be delivered to United for integration into the EMS.

EMS Demonstration Unit

The final activity under the program will be the construction and assembly of an Engineering Model System (EMS). This system will incorporate a fuel cell stack developed under the program by United and an electrolysis cell stack developed by a supplier.

The EMS unit schedule is shown in Figure 42. The schedule shows that one year will be required to procure system components, fabricate and assemble the unit. At the start of the second year of the program, the EMS unit will be available for testing.

A two-month test of the EMS will be conducted at United. The system integration test will be conducted at RFCS design conditions to demonstrate system efficiency, transient load capability and trouble-free operation. A total of 1000 cycles of Regenerative Fuel Cell Operation will be completed during the operational test.

Upon completion of the United test program the EMS will be delivered to NASA.

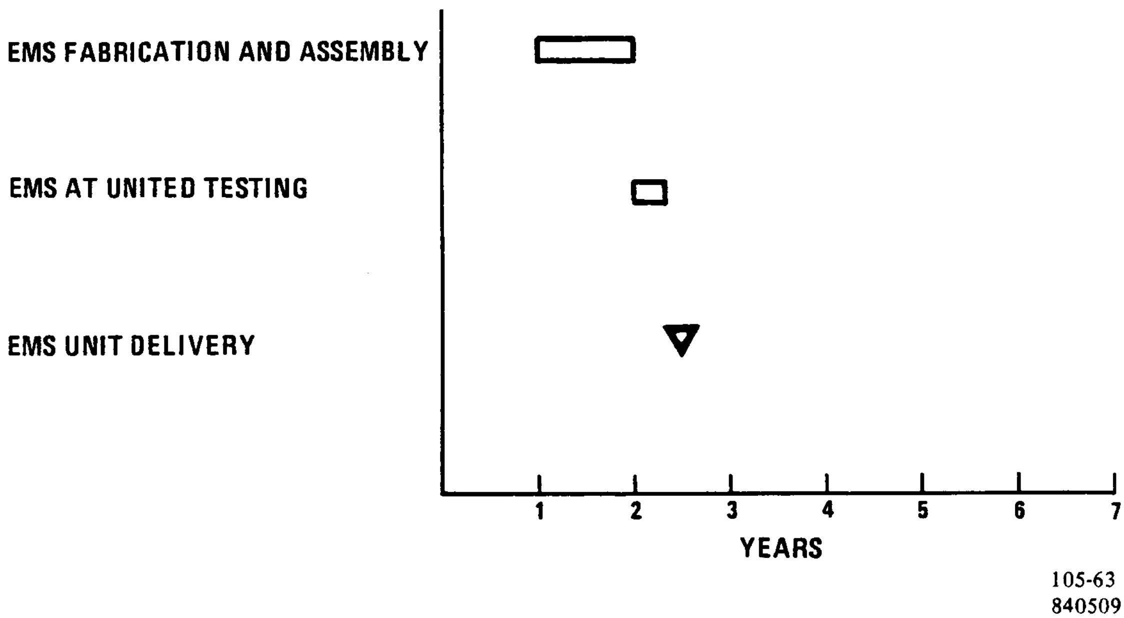

Figure 42. EMS Demonstration Unit Schedule

APPENDIX A
SYSTEM CONCEPTS

APPENDIX A

SYSTEM CONCEPTS

This section describes the evolution of the baseline regenerative fuel cell system described in this report. Initially, several system options were evaluated against such characteristics as weight, volume, complexity, development risk, reliability and cost. From that group, two systems were selected for further consideration. These are shown in Figures 43, 44, and 45.

The system shown in Figures 43 and 44 represents the most straightforward possible integration of a fuel cell power plant and an electrolyzer with provisions for the cyclic storage of gaseous and liquid reactants and the capability of thermal integration. Furthermore, it represents, in every respect, proven technology. Basically, it consists of a fuel cell of the Orbiter type, and an electrolyzer unit of either the alkaline static feed type or acid solid polymer electrolyte type. These are connected together via pressurized storage tankage for the reactant gases produced by the electrolyzer and water storage tankage for reactant water produced by the fuel cell. Each unit has its own coolant loop and interface heat exchanger to permit rejecting waste heat to the spacecraft coolant loop. An inter-unit heat exchanger, in communication with both coolant loops, permits heat exchange between the fuel cell unit and electrolyzer unit.

The advantages attributed to this system are low development risk, high performance confidence, easy resupply of lost reactants and a substantial data base.

The system shown in Figure 45 represents an advanced concept deemed worthy of further development for space station type missions. It still retains separate fuel cell and electrolysis cell stacks, but they are much more closely integrated and the number of required components is reduced.

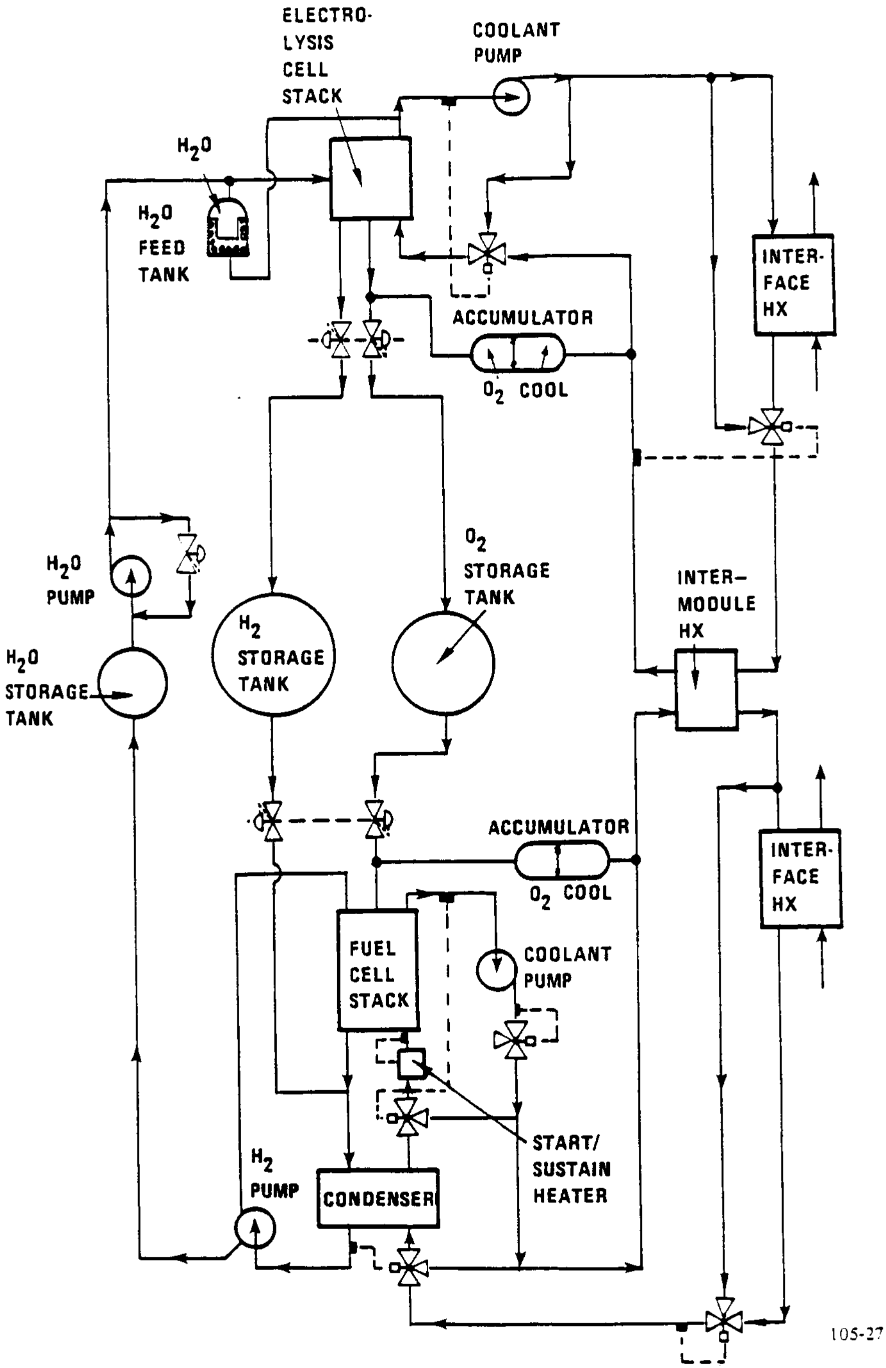

Figure 43. Regenerable Fuel Cell - Baseline System With Alkaline Electrolyzer

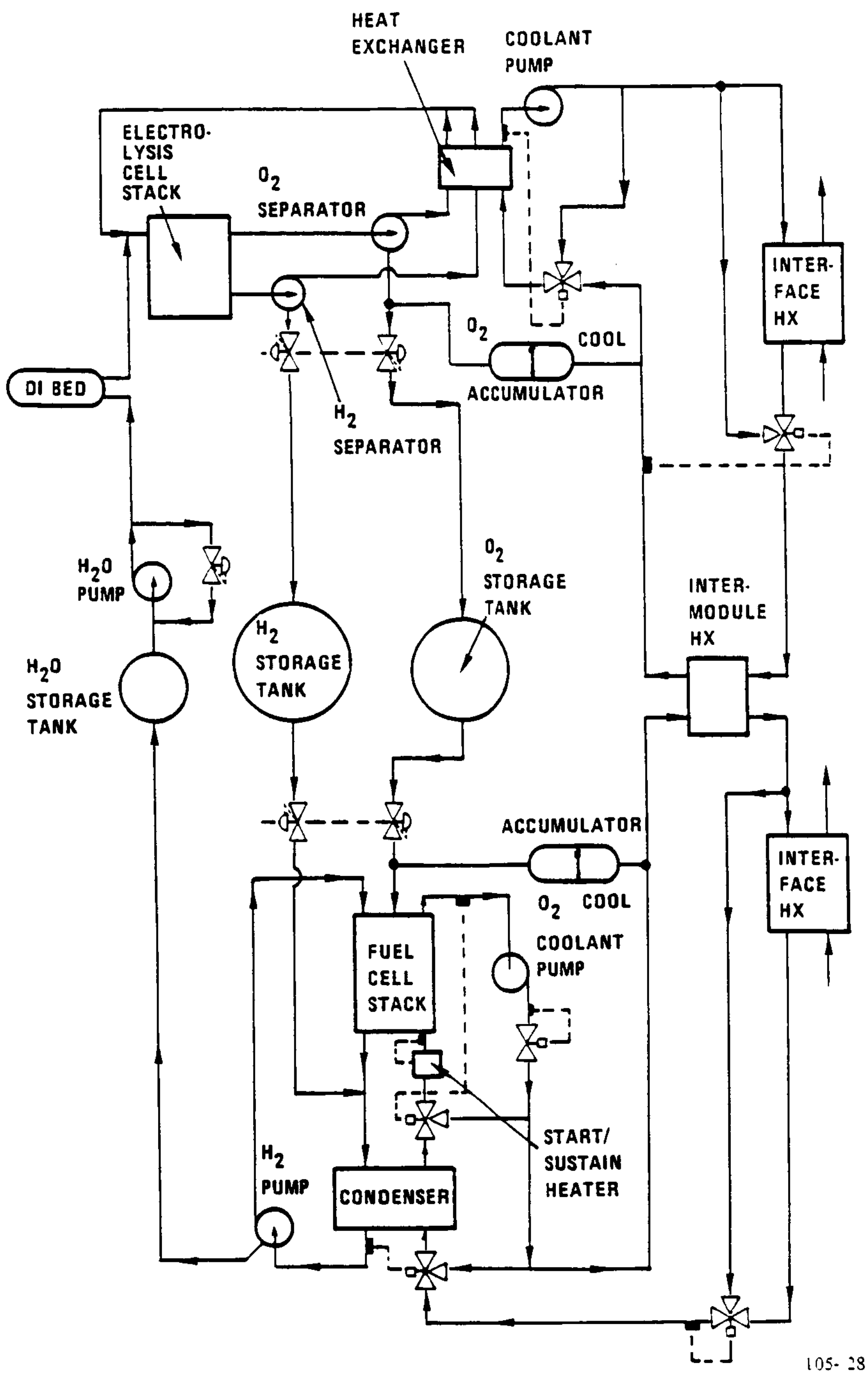

Figure 44. Regenerable Fuel Cell - Baseline System
With Acid Ion Exchange Membrane Electrolyzer

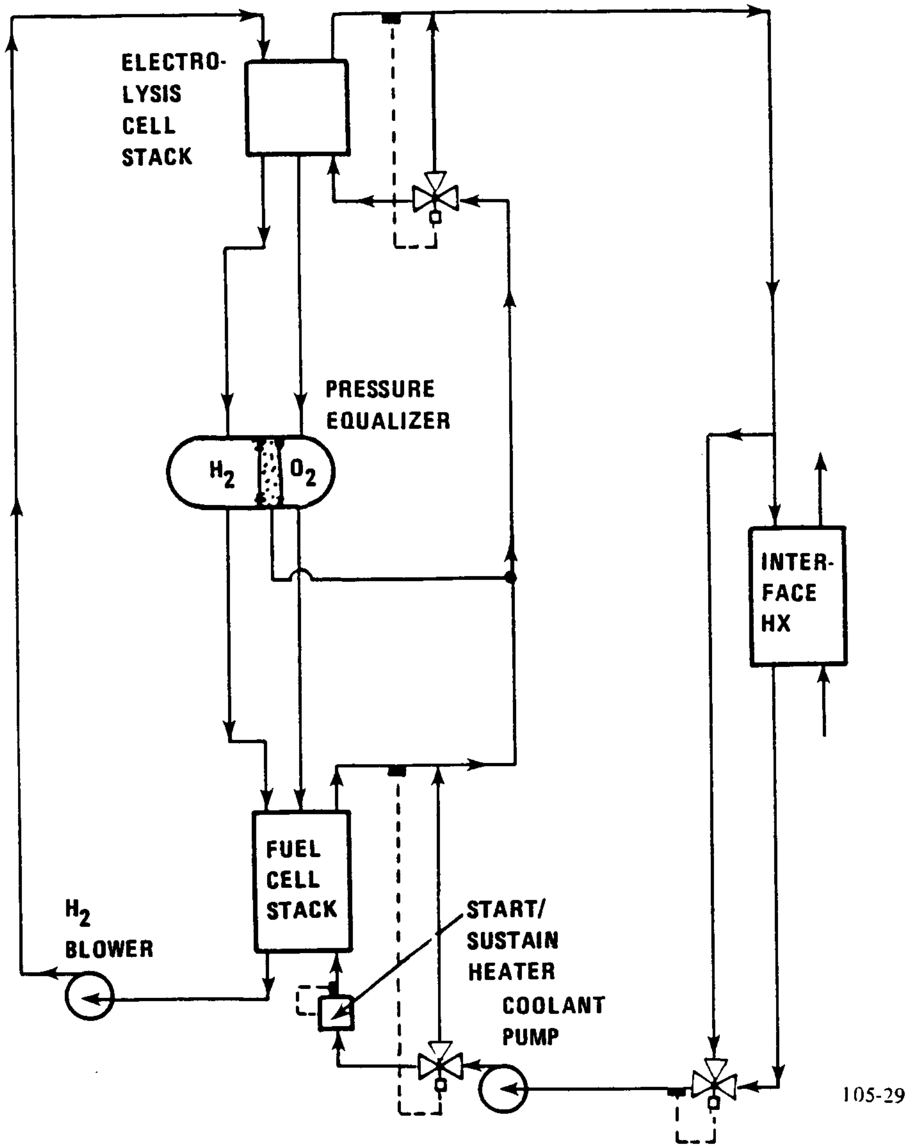

Figure 45. Regenerable Fuel Cell - Advanced, Simplified System

C - 2

In this concept, a common recirculating hydrogen loop with a blower passes a constant flow of hydrogen through each cell stack. Water produced in the fuel cell during discharge is distributed by the flowing hydrogen and stored in porous reservoir plates in each stack. Reactant gases are provided from a dual-fluid accumulator which communicates with the hydrogen recirculation loop on one side and a common oxygen line between the two cell stacks on the other side. As reactants are consumed in the fuel cell stack, the gas pressure in both stacks, accumulator and connecting lines drops.

During charge, water stored in each cell stack is electrolyzed with the transfer from the fuel cell stack to the electrolysis cell stack being accomplished by the recirculating hydrogen stream. The gases produced in the electrolyzer are stored in the accumulator, cell stacks and piping causing the total system pressure to rise. Thus, during the cyclic operation of this system, the total system pressure rises and falls while the amount of water stored within the cells falls and rises.

The cell stacks are cooled or heated, as required, by means of a common coolant loop that passes first through the fuel cell stack, then the electrolysis cell stack and, finally through an interface heat exchanger where waste heat is rejected to the spacecraft coolant loop. A bypass around the interface heat exchanger and an electric heater in the coolant line provide the means of heating the cell stacks during startup and low load periods. Coolant loop pressure is referenced to the system pressure through the accumulator.

This system requires significant design modifications to the fuel cell stack and electrolysis cell stack to accommodate the variable pressure operation and intra-cell water storage associated with this concept.

System simplicity is the major advantage offered by this concept, but it also should provide a significant reliability improvement and may provide lower weight. The principle disadvantage appears to be higher development risk and the lack of a significant data base.

The first of these two systems that was chosen as the preliminary baseline and subjected to further analysis. In particular, the methods of managing the fuel cell product water and the methods of managing the electrolysis cell product gases were studied in considerable detail and the results of those studies incorporated in the baseline design. These studies are presented below.

A. Management of Fuel Cell Product Water

This section summarizes the results of a study of the management of fuel cell product water in a regenerative fuel cell system. Specifically, the study focused on:

- Methods of condensing the product water.
- Methods of preventing the evolution of H_2 from the product water.
- Methods of product water storage in zero-G.
- Methods of product water separation from H_2 carrier gas.

Methods of Condensing Fuel Cell Product Water - Fuel cell product water is removed from the cells in vapor form and this vapor must be condensed for efficient storage in a regenerative system. The removal of the vapor from the cells can occur in one of two ways depending on the cell design: in a conventional design, it is removed via a circulating hydrogen carrier gas; in the passive water removal design, the vapor is removed directly from a low pressure cavity within the cell.

Although condensation of the product water vapor in both cases involves a heat exchanger, it is the design of the heat exchanger and nature of the condensation process that is of interest.

In systems utilizing a carrier gas, the condenser, even in zero-g, can be of a relatively conventional design. Further, it can be relatively lightweight because it is required to function only as a condenser, and it requires little or no maintenance. The location of the condensed water in zero-g is controlled by the flow of the carrier gas which sweeps it out of the condenser into the exit piping from where it can be removed from the carrier gas in a separate device as is done, for example, in the Orbiter fuel cell power plant. The subject of water vapor separation will be discussed later. Figure 46 depicts this type of simple condenser.

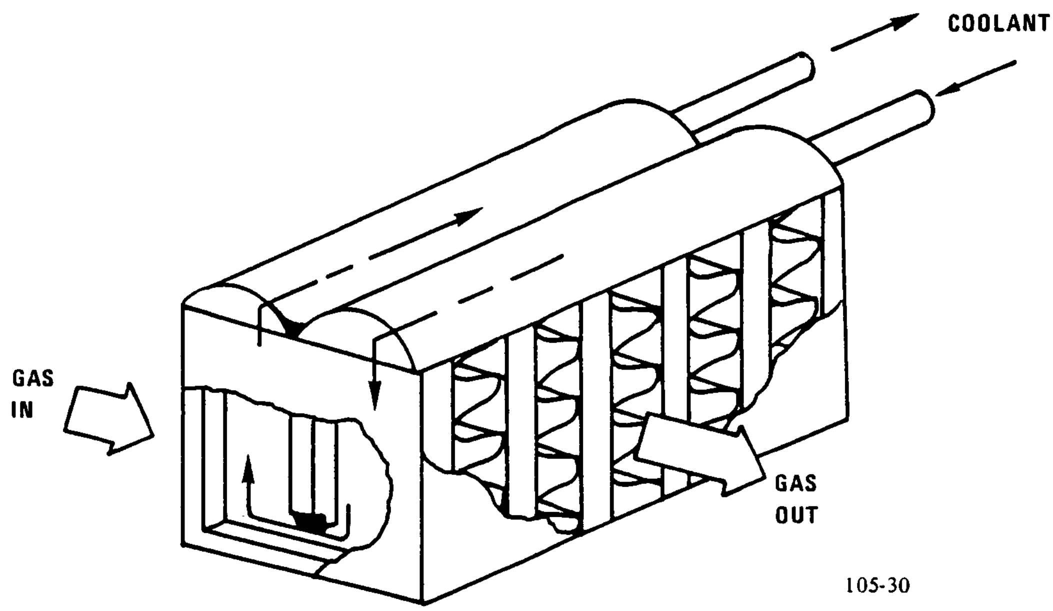

Figure 46. Condenser

In passive water removal systems, the condenser must provide zero-g liquid/vapor interface control as well as the means for condensation. This interface control is generally provided by utilizing capillary forces as in a wick or porous metal plate. These wicking surfaces must be placed at or near the condensation sites and so must be an integral part of the condenser. This causes such a condenser to be both heavier and more costly. Furthermore, it may require significant maintenance because the capillary surfaces tend to plug. This type of condenser is shown in Figure 47.

It is clear that the type of condenser used is dependent on the cell design used. Since United believes that the passive water removal design is an unproven technology for relatively near terms applications, the fuel cell design for a regenerative system will employ an H_2 carrier gas for water removal and, therefore, will use a conventional condenser design.

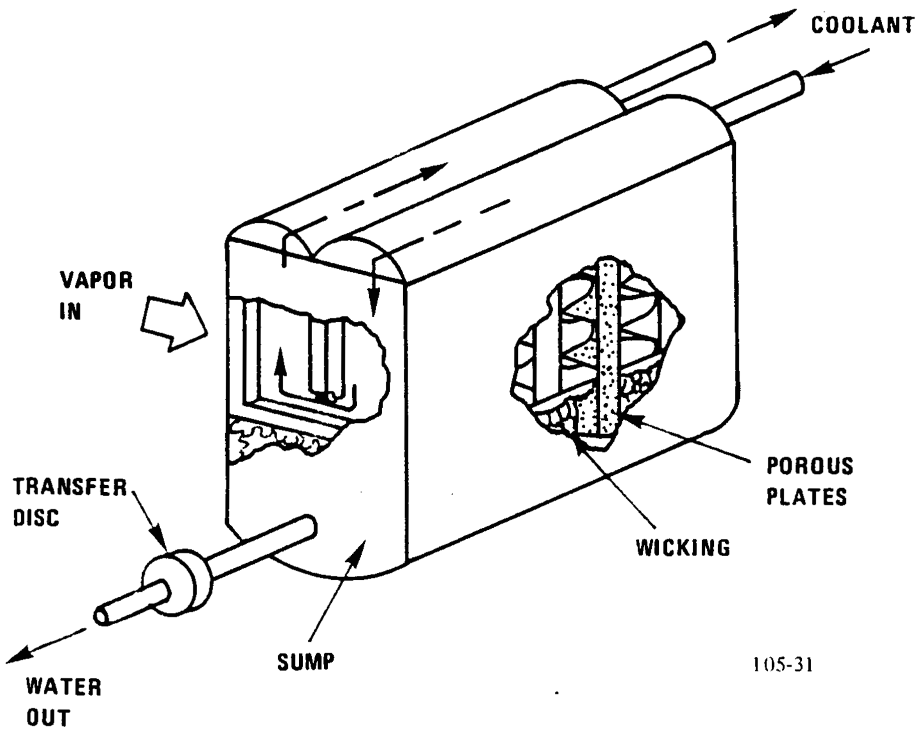

Figure 47. Static Condenser

Methods of Eliminating Dissolved H_2 Evolution from Product Waters - Water, in the fuel cell, is produced and condensed in the presence of hydrogen gas and exits the condenser saturated with hydrogen at a total pressure of approximately 60 psia (41.4 N/cm^2). As the product water passes first to the water storage tank and then through the pump to the electrolysis cell dissolved hydrogen may be evolved at any location where the pressure falls below 60 psia (41.4 N/cm^2). In addition, and more importantly, when the hydrogen laden water enters the electrolysis cell water cavity, it mixes with the electrolyte and, in the presence of KOH, loses some of its hydrogen solubility allowing gaseous hydrogen to be evolved in the water cavity. Because the amount of KOH present in the water cavity is fixed, the existence of hydrogen gas in the cavity reduces the amount of water mixed with the KOH and, hence, raises the electrolyte concentration. Eventually, this process could dry the cell out sufficiently to allow cross-over and cell failure. Thus, it is necessary to remove the dissolved hydrogen before it enters the electrolysis cell or to impose conditions which prevent its evolution.

Figures 48 and 49 show the relationship of temperature and pressure on hydrogen solubility in water. Between about 100°F (378.8°C) and 300°F (148.0°C) temperature has little effect but the pressure effect is nearly linear. From this, it is concluded that temperature variations in the system may be ignored, but pressure variations will impact the extent of hydrogen evolution in proportion to the loss of pressure. Since there is a general increase in water pressure from the fuel cell to electrolysis cell, hydrogen evolution due to pressure losses would occur only locally upstream of the pump. The water storage tank and pump inlet are possible locations for H_2 evolution. Evolved H_2 may be vented (to space) from the water storage tank should any collect there, and the H_2 evolved in the piping or pump will be redissolved as it enters the high pressure region downstream of the pump. Thus, there is no real problem imposed by the dissolved H_2 in the tank and piping except for a potential for slight cavitation at the water pump inlet or a small loss of H_2 from the tank. Nevertheless, there are methods of reducing the amount of dissolved H_2 which will be discussed later.

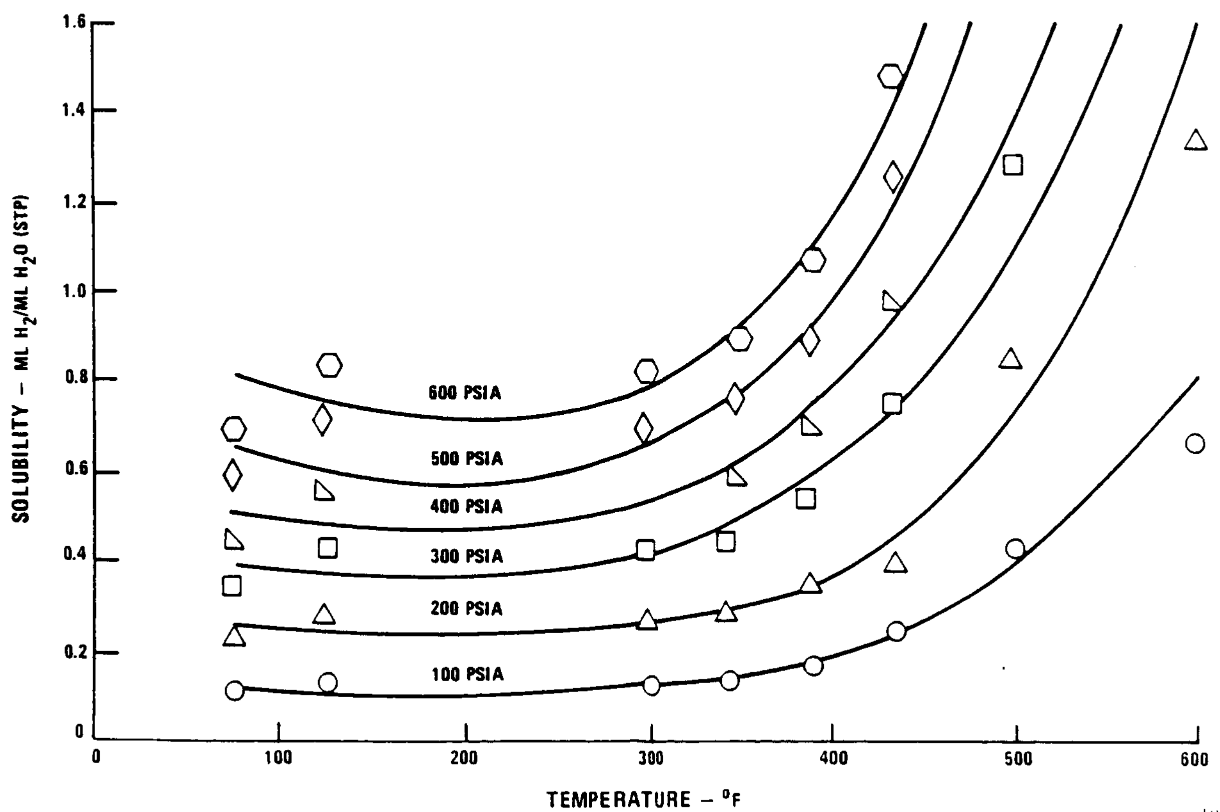

Figure 48. Solubility of Hydrogen in Water with Varying Temperature

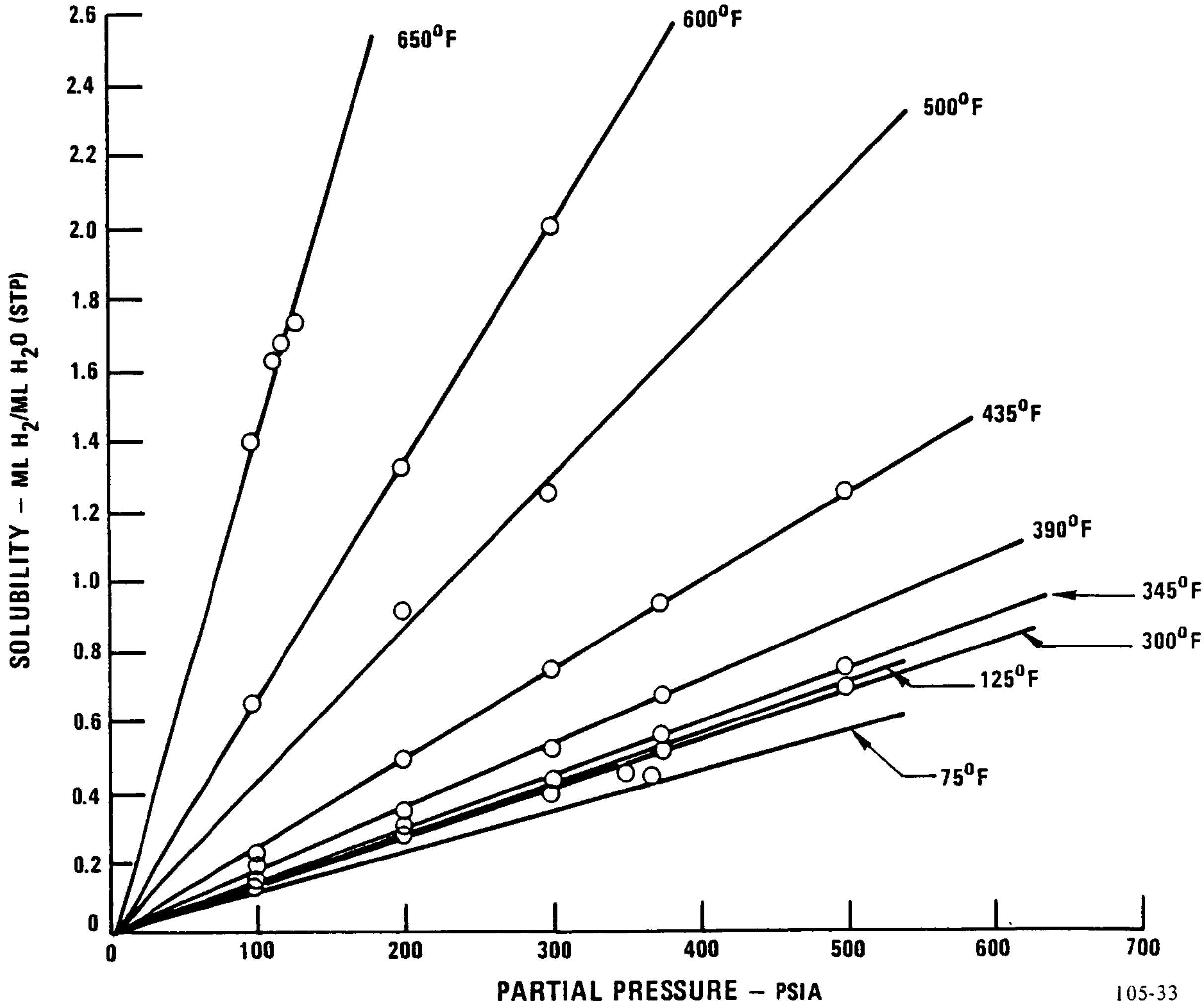

Figure 49. Solubility of Hydrogen in Water with Varying Pressure

Figure 50 shows the hydrogen solubility limit in the electrolysis cell water cavity. In this figure it is presented as the total pressure for dissolved H_2 equilibrium in a KOH electrolyte as a function of electrolyte concentration. Operation above the line implies no hydrogen evolved while operation below the line would result in some hydrogen evolution. For an electrolysis cell with an electrolyte concentration of 25% wgt KOH, an electrolysis cell pressure of 300 psia (206.8 N/cm²) or above will guarantee that no hydrogen evolution will occur from product water supplied from a fuel cell operating at 60 psia (41.4 N/cm²) and 140°F (60°C). If the operating temperature of the fuel cell is 180°F (82.2°C), the required pressure to avoid hydrogen evolution actually drops slightly to about 275 psia (189.6 N/cm²). Since high electrolysis pressure is desirable also for efficient volume storage of the product reactant gases, hydrogen evolution in the electrolysis cell is not viewed as a problem provided that the electrolysis cell is operated at 300 psia (206.8 N/cm²) or above. In the remainder of this study, a 300 psia electrolysis cell pressure was assumed.

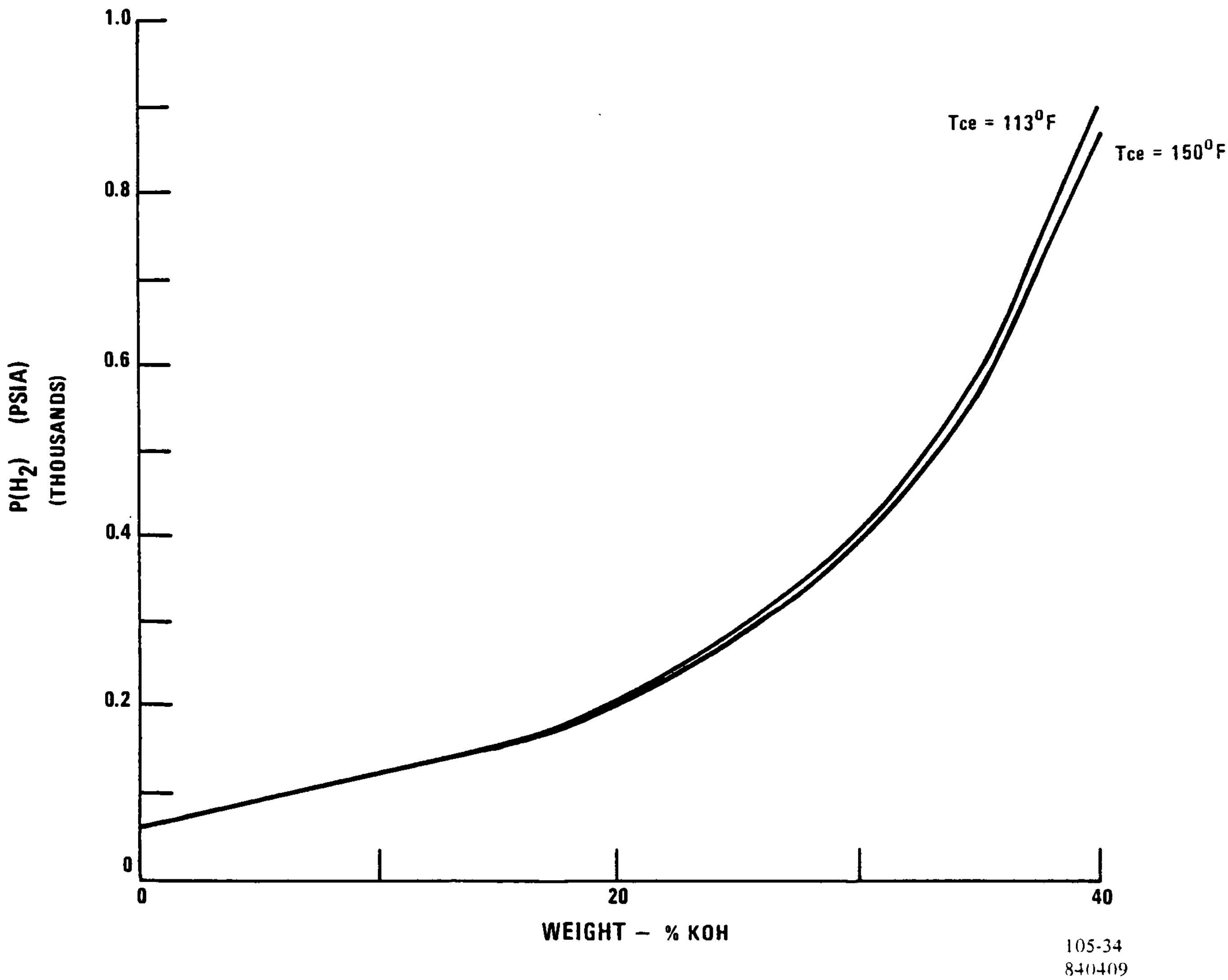

Figure 50. Pressure (H_2) in KOH for Temperature 150°F - 180°F

There are, however, two potential methods of removing dissolved hydrogen from the fuel cell product water should that action appear desirable. The first of these is a non-thermal, static degasifier employing hydrophillic and hydrophobic screens to separate hydrogen evolved by virtue of a reduced pressure on the water. Such a degasifier would be located at the lowest pressure point in the piping or at other locations such as tanks, where the hydrogen might tend to collect.

A particular configuration of this degasifier is shown in Figure 51. Water and evolved hydrogen bubbles would enter the device and pass through a particular filter included to protect the downsteam hydrophillic screens. The water would then pass out of the device through a hydrophillic screen of a sufficiently small mesh to trap the hydrogen bubbles on the upstream side. The hydrogen bubbles would remain in this space until, somewhat randomly, they reached the region where the hydrophobic screen was located. This screen would have a high enough bubble point to prevent water flow, but would allow the gas to escape readily. The removed hydrogen could then be pumped back into the hydrogen storage tank or dumped overboard. Such a device is simple, has no moving parts and imposes no thermal requirements.

The second method of removing hydrogen is with a steam degasifier. This process involves heating the product water to the boiling point and allowing a very small amount of the steam escape (to space). With steam will go a large quantity of the dissolved hydrogen providing more than ample margin. Figure 52 shows a schematic of the arrangement utilizing a regenerative heat exchanger and an electrical heater. Figure 53 shows the degasification thermal requirements to prevent hydrogen evolution in the electrolysis cell as a function of electrolysis cell operating pressure and product water temperature. It was assumed that above 300 psia (206.8 N/cm^2), no degasification is required. Although this process provides positive hydrogen removal, it is thermally wasteful in spite of the regenerator and adds significant complexity to the system.

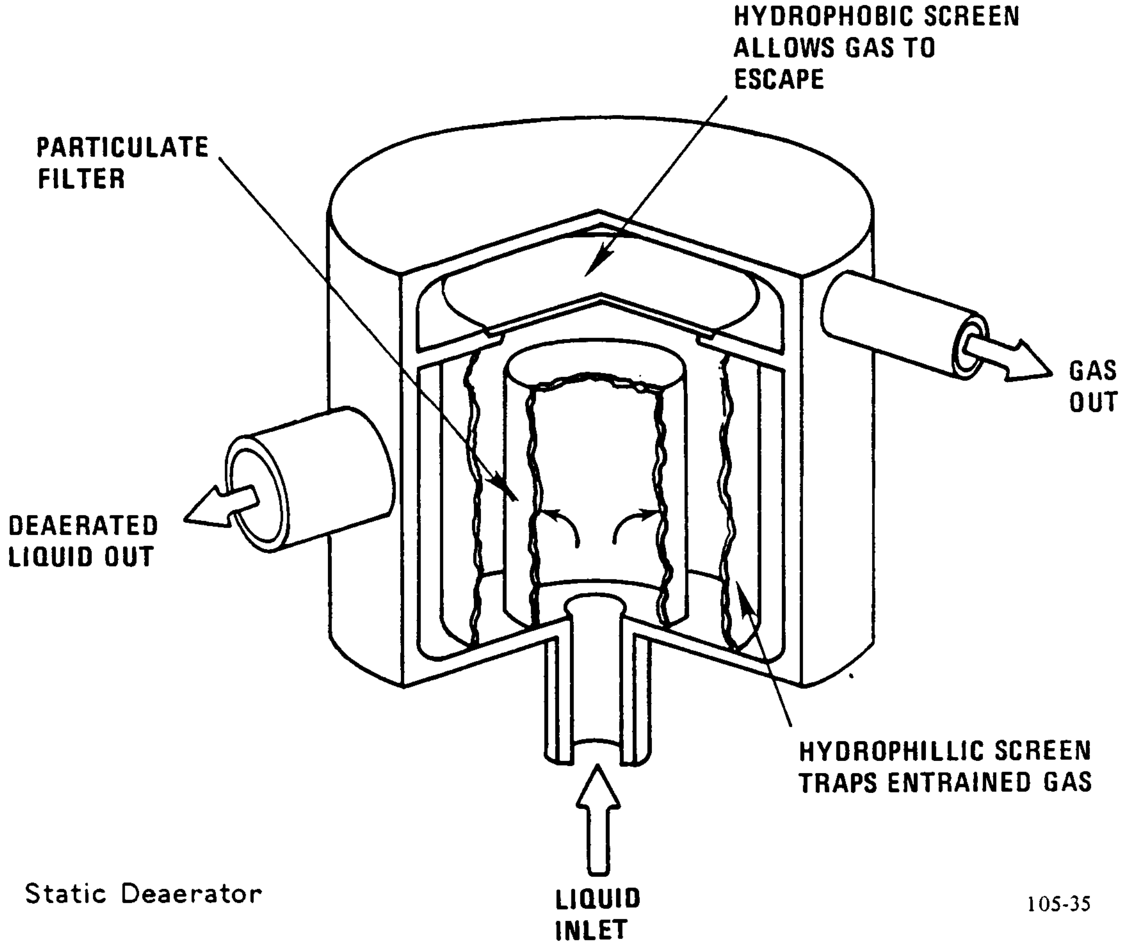

Figure 51. Static Deaerator

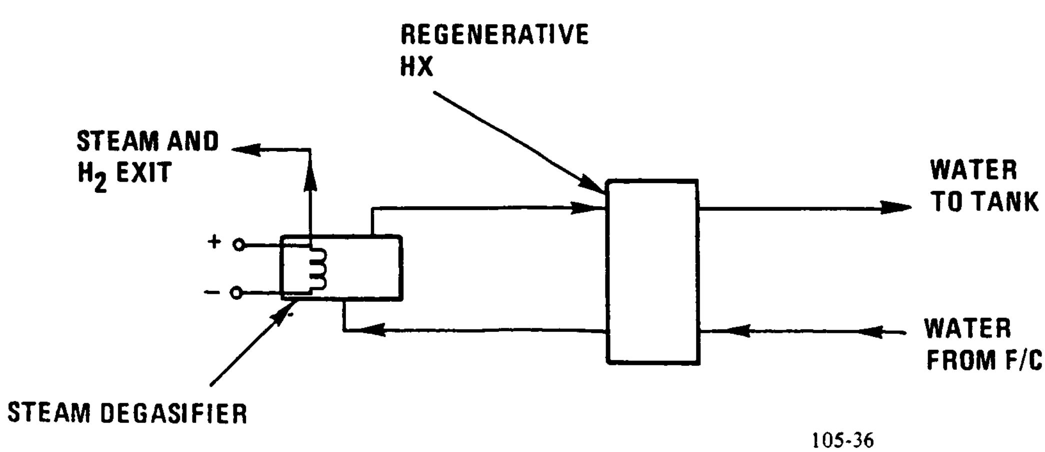

Figure 52. Steam Degasifier Schematic

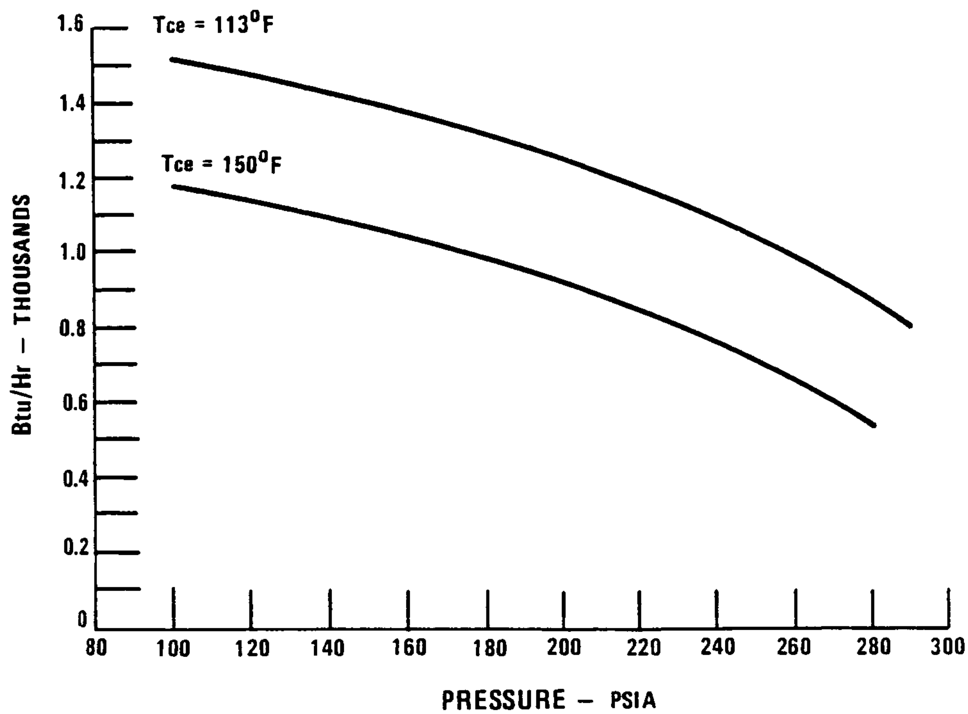

Figure 53. Steam Degasifier Thermal Requirements

This study resulted in the decision to handle the problem of hydrogen evolution in the electrolysis cell by operating the electrolysis cell at 300 psia (206.8 N/cm^2) or above. Hydrogen evolution in the piping is not viewed as sufficiently serious to warrant the use of special removal devices to prevent it.

Product Water Storage - A requirement of the product water storage equipment is that it be able to deliver a uniform, gas-free, supply of liquid water to the electrolysis cell. This means that the storage tank must be able to positively locate the water contiguous with the exit port at all times.

There are two basic methods of accomplishing this in zero-g. The first is to employ a storage tank which is fitted with a flexible bladder. The water is stored on one side of the bladder while a pressurizing gas or a spring exerts a steady force on the opposite side. As water enters or leaves the tank, the bladder expands or collapses to accommodate the change in volume and also holds the water, of whatever quantity, in contact with the exit port. Such an arrangement is depicted in Figure 54.

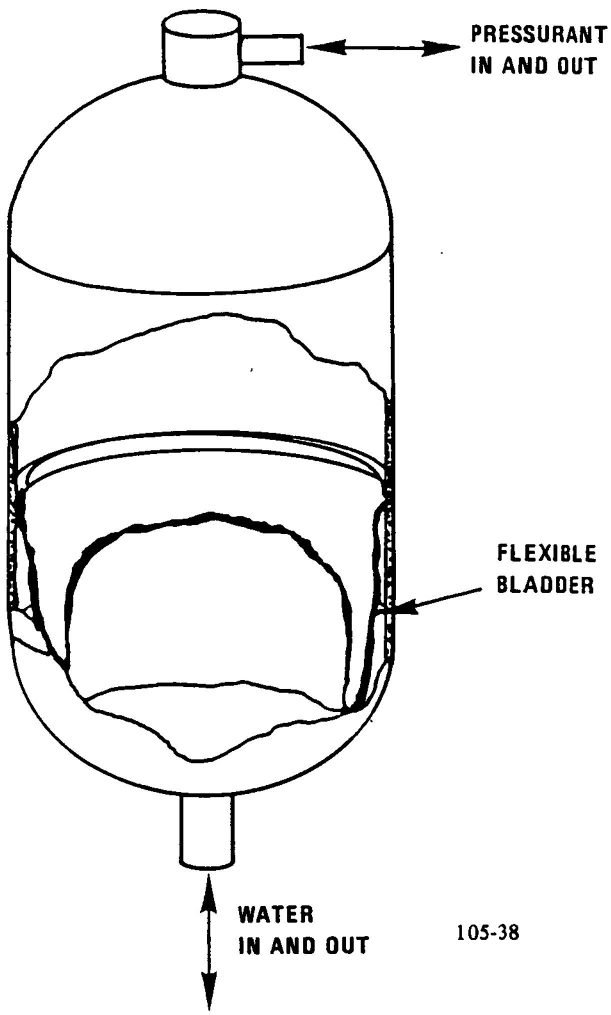

Figure 54. Bladder Tank

Bladder tanks have been used on previous space missions and provide positive positioning and expulsion of the stored material. They also provide the means (bladder position) for accurate stored quantity sensing. Most of the problems with bladder tanks lie with the bladder itself. Continuous flexing of the bladder material leads to poor life characteristics and bladder failures are difficult to detect and correct in zero-g.

The second type of water storage tank relies on surface tension effects (capillary forces) for liquid positioning. One configuration for this type of tank is shown in Figure 55. Here, a tank with a conical cross-section at the exit port is filled with conical baffles such that the space between the baffles decreases as the exit port is approached. Water entrained between the baffles will tend, due to surface tension, to fill the smaller spaces and thus will be moved to and held in proximity to the exit port. A hydrophillic screen of a proper mesh size would provide a seal against the passage of evolved gases into the water piping, and a hydrophobic screen opposite the exit port would allow evolved gases to escape while retaining

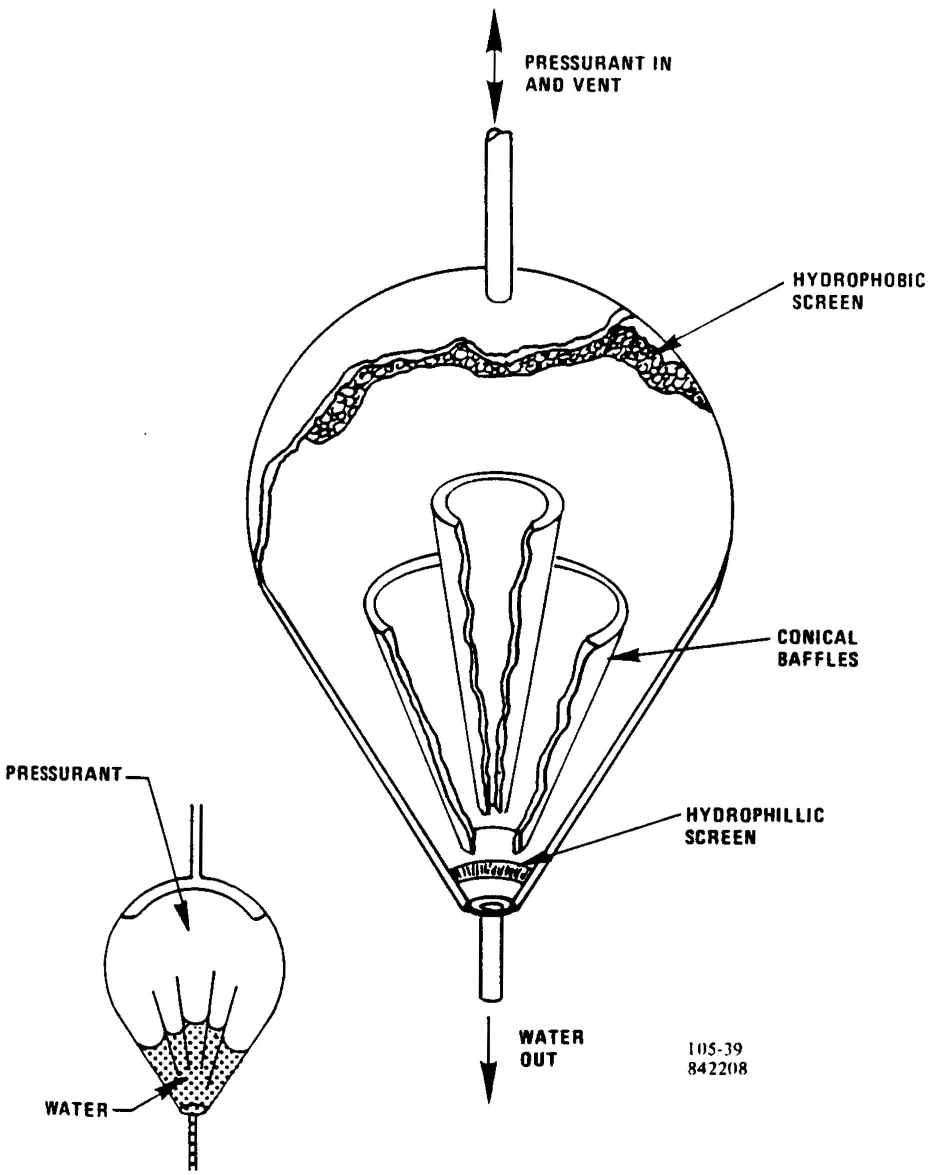

Figure 55. Bladderless Tank

the water. A variant of this design could employ wicking whose pore size decreases toward the exit port to accomplish the same purpose. The operating life of the tank could be limited by plugging of the small pores within the wick.

Bladderless tanks have not been proven in space although there does not appear to be any fundamental reason why they would be unsuitable. Reliability should be high, but accurate quantity sensing might prove difficult.

Both types of water storage tank can be seriously considered for this application. The choice depends as much on the particular configuration of the system as on cost or development factors. For example, either type may be used in a system having a rotary water separator that delivers the water to the tank at a positive head differential while only the bladder tank fitted with a spring can be conveniently used in a system where water separation results in pressure loss. This topic will be dealt with in more detail in the next section.

Product Water Separation - Zero-g separation of the product water from the hydrogen carrier gas can be accomplished either by inducing local artificial gravity by means of a rotating drum where separation occurs, or by relying on surface tension effects as occur in wicks and screens.

The method used in conventional fuel cell power plant design employs a motor driven rotating separator as an integral part of the hydrogen recirculating pump. This is depicted in Figure 56. It is the separating technique used in the Orbiter fuel cell powerplant. As the moisture laden gas passes through the separator, the water droplets impinge on rotating vanes or perforated disks and are flung outward to the walls of a rotating drum. A stationary "pitot" tube picks up the water from the drum and delivers it to the storage tank at a slightly elevated head induced by the velocity of the water past the tube opening. Such a separator provides positive interface control, virtually no gas carry-over and a positive liquid pressure head. It requires power and exhibits the somewhat lower reliability typical of rotating machines.

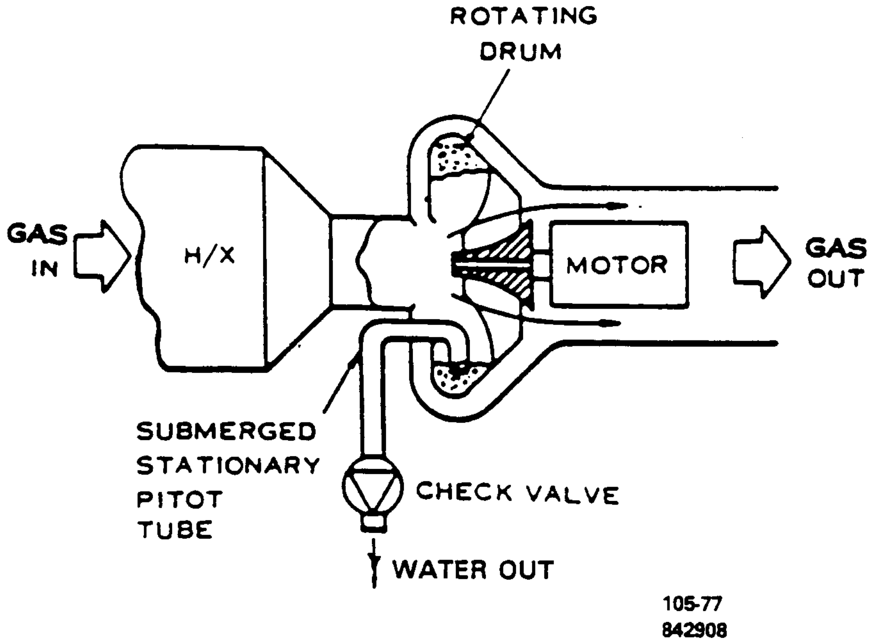

Figure 56. Motor Drive Rotating Separator in H_2 Recirculating Pump

There are a number of potential configurations of separators using wicks or screens. In those using wicks or porous metal plates, the water droplets are collected by impingement, or the vapor is condensed on the porous surface. In either case, the small pore size of the material holds and transports the water, via a pressure drop, to the storage tank feed pipe. Figures 57 and 58 show the use of wicks in conjunction with the condenser; in one case, as an integral part of the condenser and in the second case, as an added section immediately at the condenser exit. Figure 59 depicts an elbow wick separator which, as shown, may be located some distance from the condenser. Preliminary design estimates indicate that the elbow wick arrangement is somewhat smaller and lighter than arrangements in which the wicks are associated with the condenser.

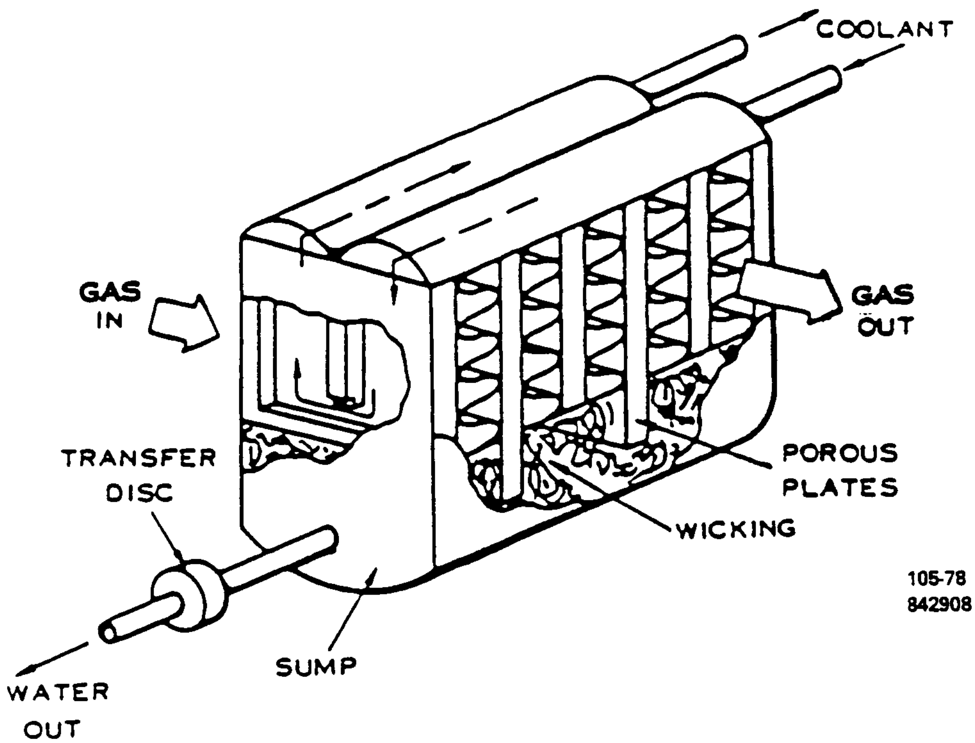

Figure 57. Integral Wick Condenser

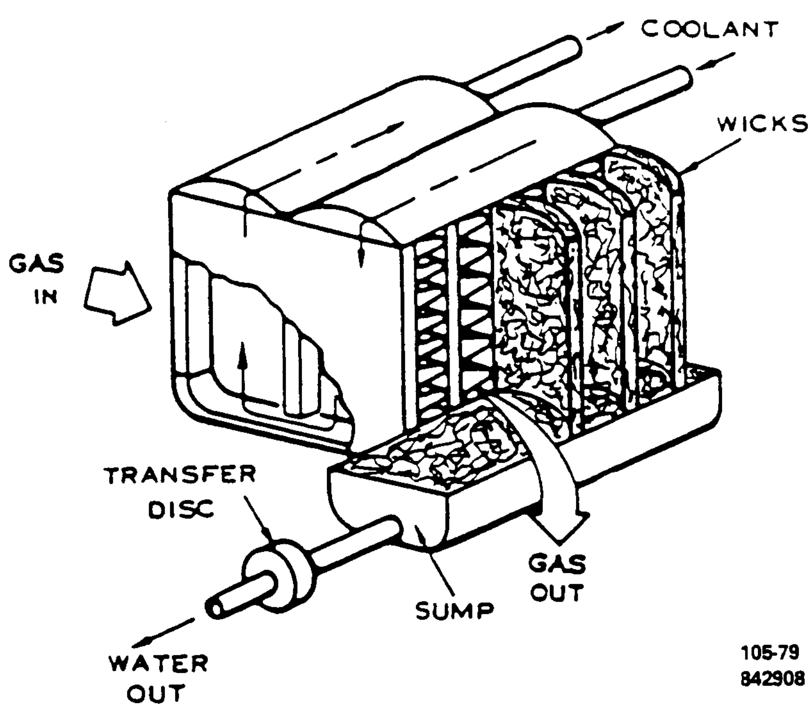

Figure 58. Face Wick Condenser

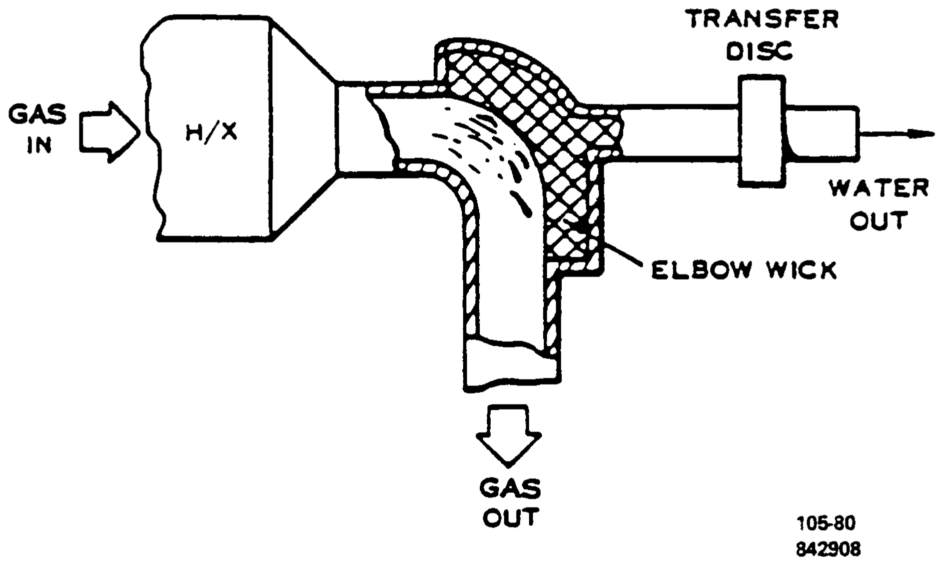

Figure 59. Elbow Wick Separator

A conical hydrophobic screen may also be used to separate out the condensed water. This is shown in Figure 60. The mesh size of the screen must be such that the pores are smaller than the water droplets to be collected. Due to the hydrophobic nature of the screen, the droplets will refrain from filling the pores and will be swept along the cone to a wick filled chamber at the base of the cone around the duct wall. Hydrophobic surfaces unfortunately tend to lose their hydrophobic character with time (due to contamination of the liquid) so that the life of this type of device is unpredictable. It must certainly be a replaceable item. All of these designs require a pressure drop between the separator and the storage tank so that the tank pressure must be maintained less than system pressure.

Based on these considerations, a motor-driven centrifugal separator appears appropriate for near-term applications while an elbow-wick separator coupled with the spring-loaded bladder storage tank may be more desirable for future applications.

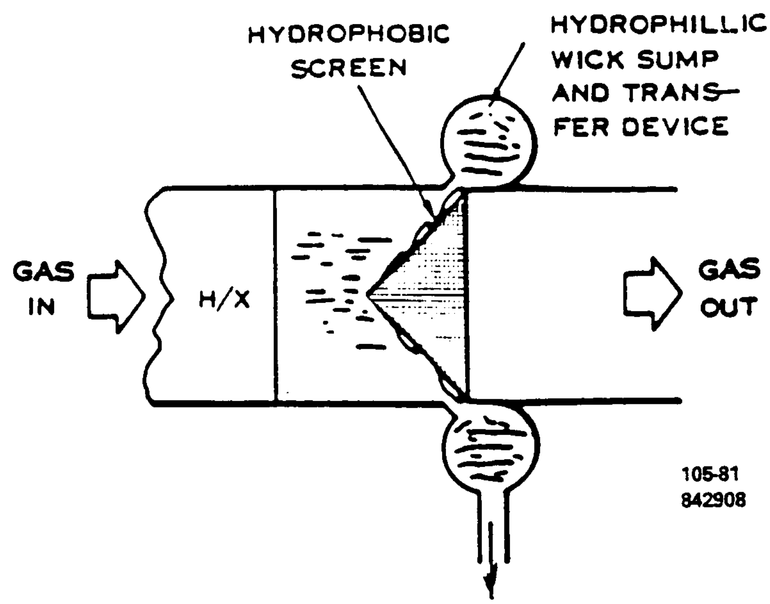

Figure 60. Hydrophobic Screen Separator

B. Reactant Storage Subsystem

This section summarizes the results of a study of the management of the gaseous reactants produced by the electrolysis cell and consumed by the fuel cell in a regenerative fuel cell system. Specifically, the study focused on:

- methods of avoiding condensation of water vapor from the reactant gases in the piping and storage tanks
- sizing of reactant storage tanks
- thermal requirements of reactant storage tanks

Methods of Avoiding Unwanted Condensation - The gaseous reactants, hydrogen and oxygen, produced in the electrolysis cell exit the cells with a water vapor partial pressure in equilibrium with the electrolyte at cell operating temperature. For an electrolyte concentration of 25% wgt KOH, the water vapor partial pressure in the reactant gases would be 2.0249 psia at 140°F and 5.357 psia at 180°F. The corresponding dew points are about 127°F and 165°F, respectively. Because of this significant quantity of water vapor, reactant gas transport and storage presents a problem in zero-g because of the possibility of condensation as temperatures and pressures vary.

Furthermore, in view of the fact that the fuel cell utilizes an aqueous solution of KOH as the electrolyte, the desirability of providing humidified gas to the fuel cell is worthy of consideration.

Although the reactant hydrogen may be introduced into the fuel cell recirculating hydrogen loop either upstream or downstream of the condenser, it is in either case mixed with a high flow humidified gas stream. In this case, whether the reactant hydrogen is humid or dry, the impact on the fuel cell is negligible, and at most, might alter the electrolyte concentration slightly. Any additional moisture added to the fuel cell in either stream will impact the size of the condenser, but only marginally. Thus, it is relatively immaterial whether the hydrogen stream is humidified or not.

In past fuel cell application, the reactant oxygen has been supplied bone dry, generally from cryogenic supplies. Initially, this resulted in excessive drying of the cell at the oxygen inlet, but improvements in cell design readily solved the problem, and bone dry oxygen is now well tolerated by the cells. Fully saturated oxygen, on the other hand, might wet the fuel cell oxygen inlet unacceptably if introduced at fuel cell operating temperature. However, electrolysis cell oxygen from an alkaline electrolyzer is not fully saturated and could do no worse than reducing the inlet electrolyte concentration to 25% wgt KOH (at the same temperature) which is acceptable. Thus, while dehumidifying the oxygen stream would be acceptable, there is no need to do that in this application. In the case of an acid solid polymer electrolyzer, the oxygen stream exits the electrolyzer fully saturated at the exit temperature. If that temperature is reduced as can be easily done by locating the gas separator after the stack cooler then the water vapor partial pressure in the oxygen can be reduced to an acceptable level with only minor system changes.

Thus, it emerges that the only concern relating to the humidity in the reactant gases lies in the area of unwanted condensation in the piping, pressure control valves and storage tankage. Three methods of dealing with this problem were considered: moisture removal by condensation, moisture removal by the use of dessicants, and preventing condensation altogether by temperature control in the piping, pressure control valves and tanks.

Condensation - Figure 61 shows an arrangement to allow condensing water from the reactant gas streams at the electrolyzer exit. Not all of the water can be removed because in no case can the streams be cooled below the freezing point of the water. From a practical point of view, 40°F is about the lower limit. Cooling would be provided by the spacecraft coolant loop.

In addition to the condensers, it would be necessary to provide a reheater in each stream and it would still be necessary to heat the regulators and tanks directly since the temperature drop associated with the pressure loss would cool the streams far below the 40°F dewpoint of the gas. In short, not enough water vapor can be removed by condensation alone to adequately protect the equipment.

Dessicants - To overcome the inability of condensers to remove an adequate amount of water, two dessicant beds could be employed. An arrangement employing dessicants is shown in Figure 62. Here, during the charge cycle, condensers are used upstream of the dessicants to remove a large portion of the water reducing the dew point to about 40°F. The dessicant beds would then dry the reactants further to about -75°F. This would completely eliminate any spurious condensation in the storage tanks.

During the discharge cycle, the stored reactants could be delivered to the fuel cell dry while the dessicant beds were desorbed to space losing the water from the system, or, as shown, the water adsorbed on the beds could be heat desorbed back into the reactant streams and ultimately returned to the system via the fuel cell unit condenser. To prevent condensation in the fuel cell pressure regulator, additional heating would be necessary and could be provided by oversize heaters in the dessicant beds.

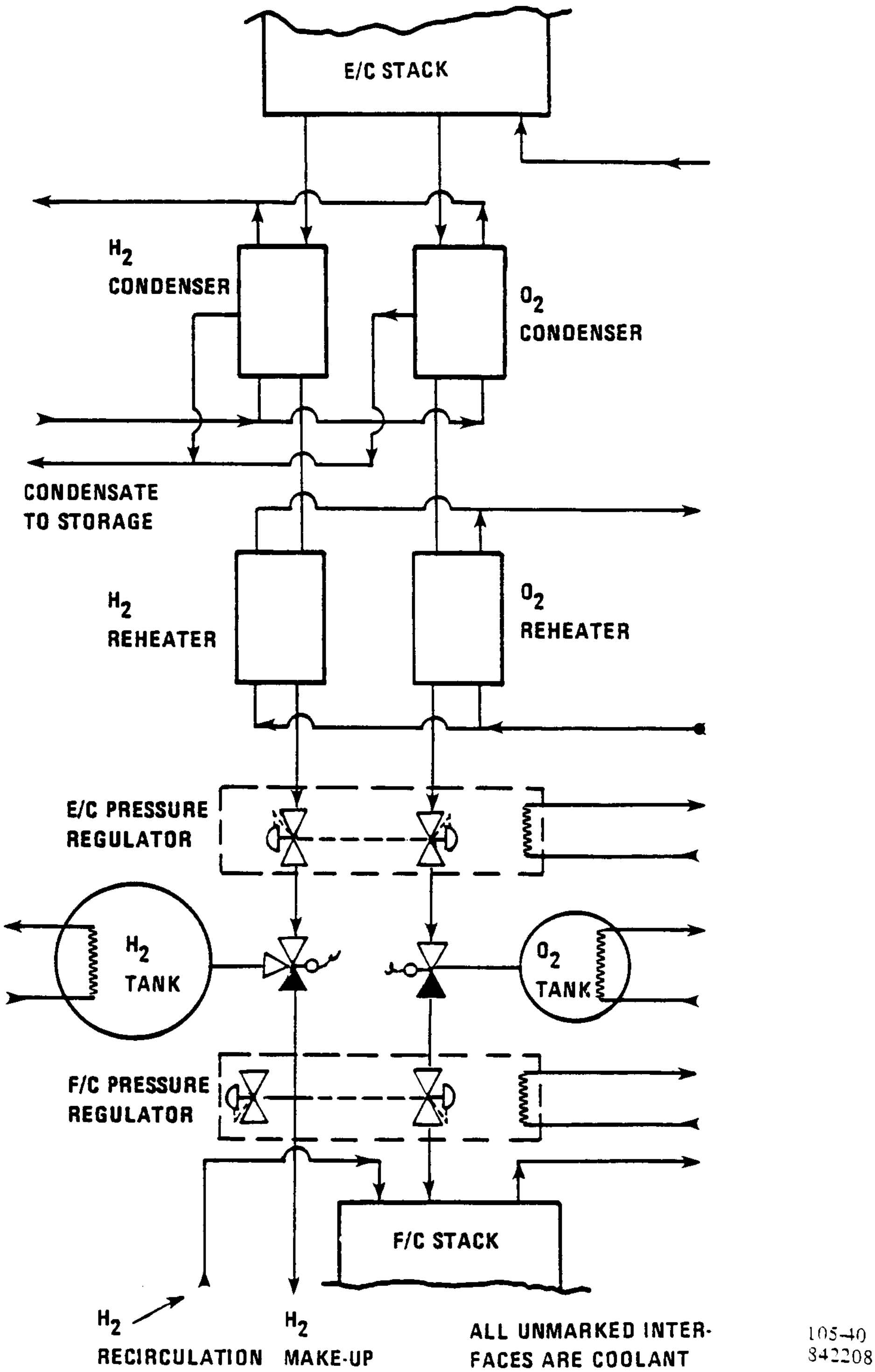

Figure 61. Reactant Gas Moisture Removal by Condensation

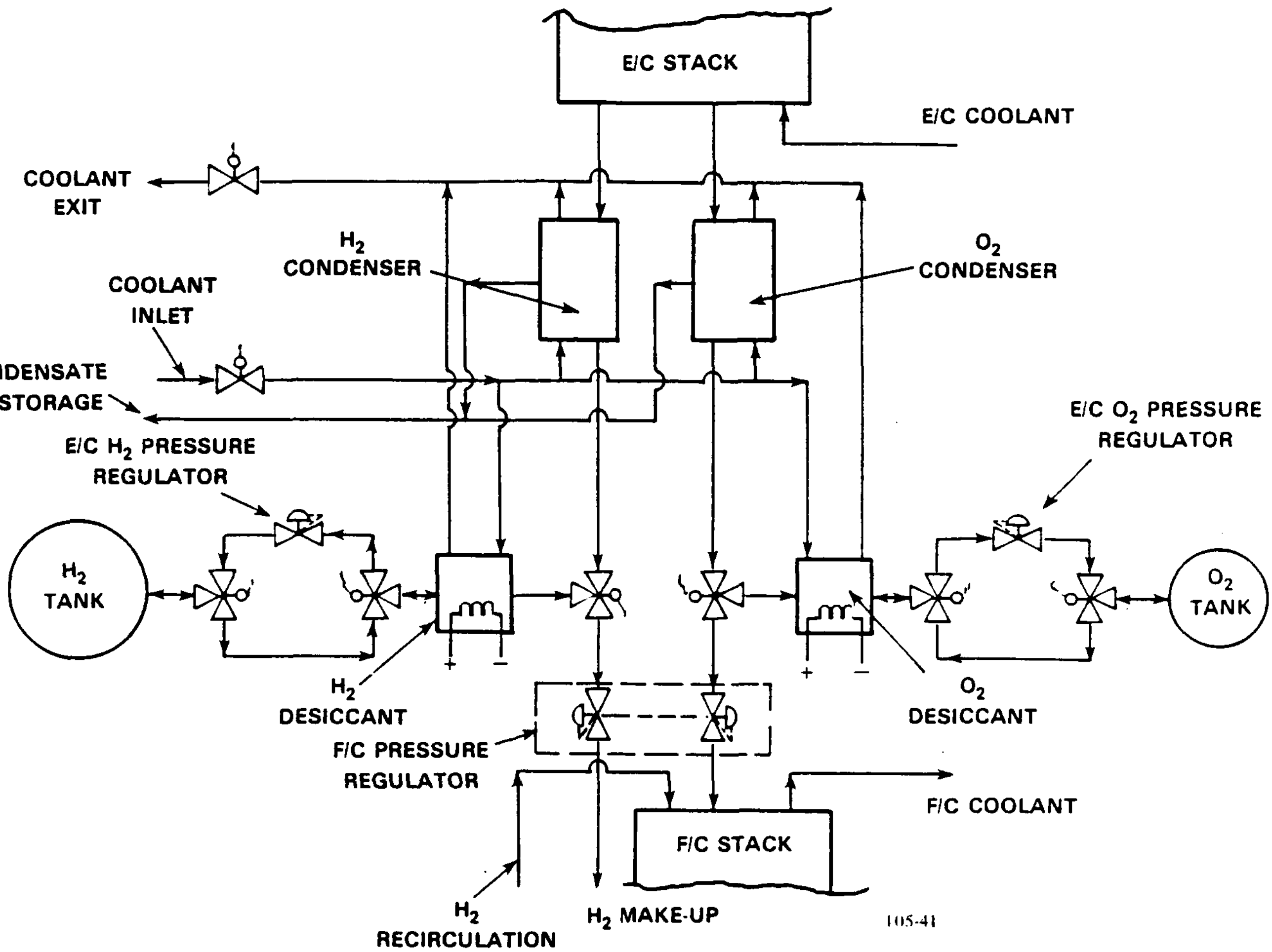

Figure 62. Reactant Gas Moisture Removal by Dessicants

Although this system would positively protect against unwanted condensation, it is deemed overly complicated and unacceptably heavy. Development of the dessicant beds, though certainly possible, would entail an unnecessary development cost.

Reactant Temperature Control - The method selected for avoiding unwanted condensation involves nothing more complicated than heating, by means of the internal coolant loop, the critical areas of the piping and tankage to keep the reactant gas temperature above the dewpoint temperature at the exit of the electrolyzer. This system is shown in Figure 63. Basically, the pressure regulators and storage tanks are all that require heating. Small pressure losses in the piping can be ignored if

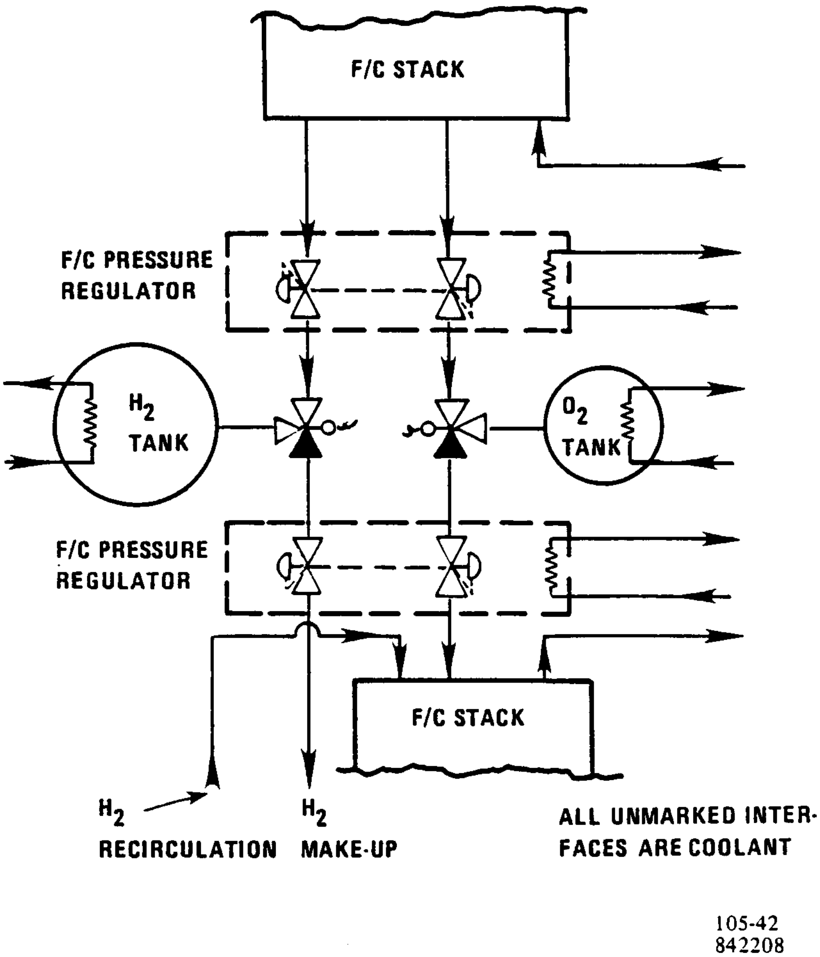

Figure 63. Reactant Gas Temperature Control

a reasonable temperature margin is maintained above the dewpoint temperature. Figure 64 shows the cyclic dewpoint variation of the reactant gases in the storage tanks as a function of electrolysis cell operating pressure and temperature. The system is simple, utilizes only fuel cell and electrolysis cell waste heat, has a low weight penalty, and exhibits high reliability.

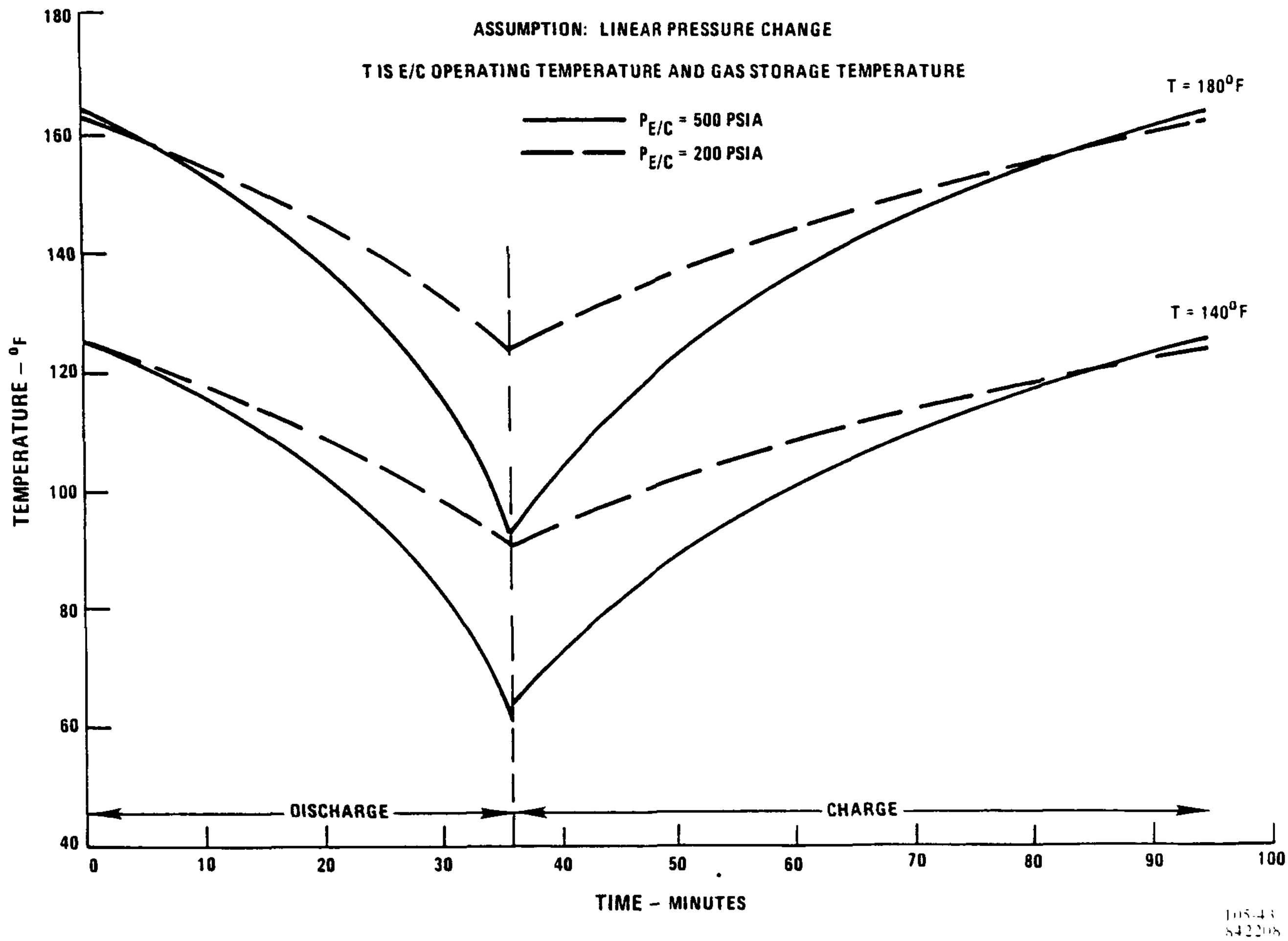

Figure 64. Dewpoint Temperature in Reactant Storage Tanks

<u>Reactant Tank Sizing</u> - Reactant storage tanks were sized to determine volume and weight characteristics and to serve as a basis for thermal requirements of reactant storage. The basis for the sizing was a 10kW regenerative fuel cell system module. Two temperature and pressure levels covering the range of interest were used as shown in Table XVI which also shows the other pertinent operational parameters.

Table XVI. H_2 and O_2 Storage Tank Sizing Parameters

Tanks were sized for two temperature levels over a range of pressures.			
Nominal:	Temperature (°F) (°C)	140 (60)	180 (82.22)
	E/C Pressure, Range (psia) (kg/cm^2)	200 - 500 (14.06 - 35.15)	200 - 500 (14.06 - 35.15)
	F/C Pressure (psia) (kg/cm^2)	60 (4.22)	60 (4.22)
Stored Quantities (Lb/Orbit)(Kg/Orbit):			
	Hydrogen	0.565 (0.256)	0.549 (0.249)
	Oxygen	4.486 (2.035)	4.359 (1.977)
Actual Tank Pressure (psia) (kg/cm^2)			
	Maximum, Range	190 - 490 (13.36 - 34.45)	190 - 490 (13.36 - 34.45)
	Minimum	70 (4.92)	70 (4.92)
Water Vapor Dew Point (°F) (°C)			
	Maximum, Range	125 (51.67)	163 - 164 (72.78 - 73.33)
	Minimum, Range	90 - 63 (32.22 - 17.22)	123 - 92 (50.56 - 33.33)

Tank weights are based on the use of Inconel as the tank material, and the essential material and configuration assumptions are shown in Table XVII.

Table XVII. H_2 and O_2 Storage Tank Weight Parameters

Material	Inconel
Shape	Spherical
Yield Strength (psi) (kg/cm^2)	125,000 (8788.38)
Safety Factor	1.5
Mounting Bracket Allowance	30%

Figures 65 and 66 show tank volumes and weight, respectively, as function of electrolysis cell operating pressure with storage temperature as a parameter.

Reactant Tank and Pressure Regulator Thermal Requirements - Because of the decision to maintain the tanks and pressure regulators where significant cyclic pressure variation occurs at constant temperature, the thermal requirements for these components were based on isothermal thermodynamic expansions and compressions of the gas.

For the storage tanks which have a significant surface area, heat loss to the ambient was also included for both uninsulated and insulated tanks. The insulation chosen was similar to that used on the Orbiter powerplant, but in a greater thickness. The assumptions used for the determination of storage tank thermal requirements are summarized in Table XVIII.

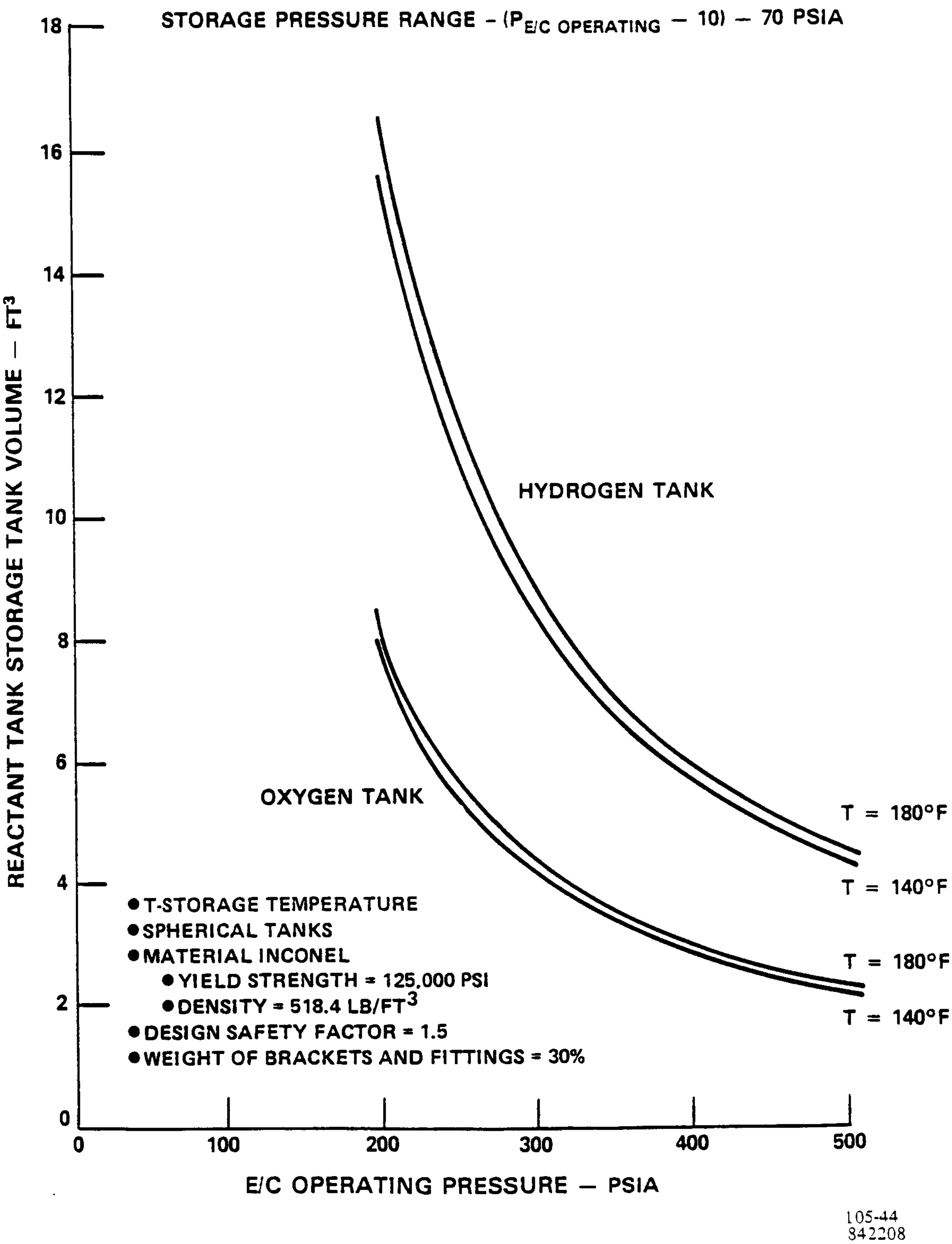

Figure 65. Reactant Storage Tank Volume

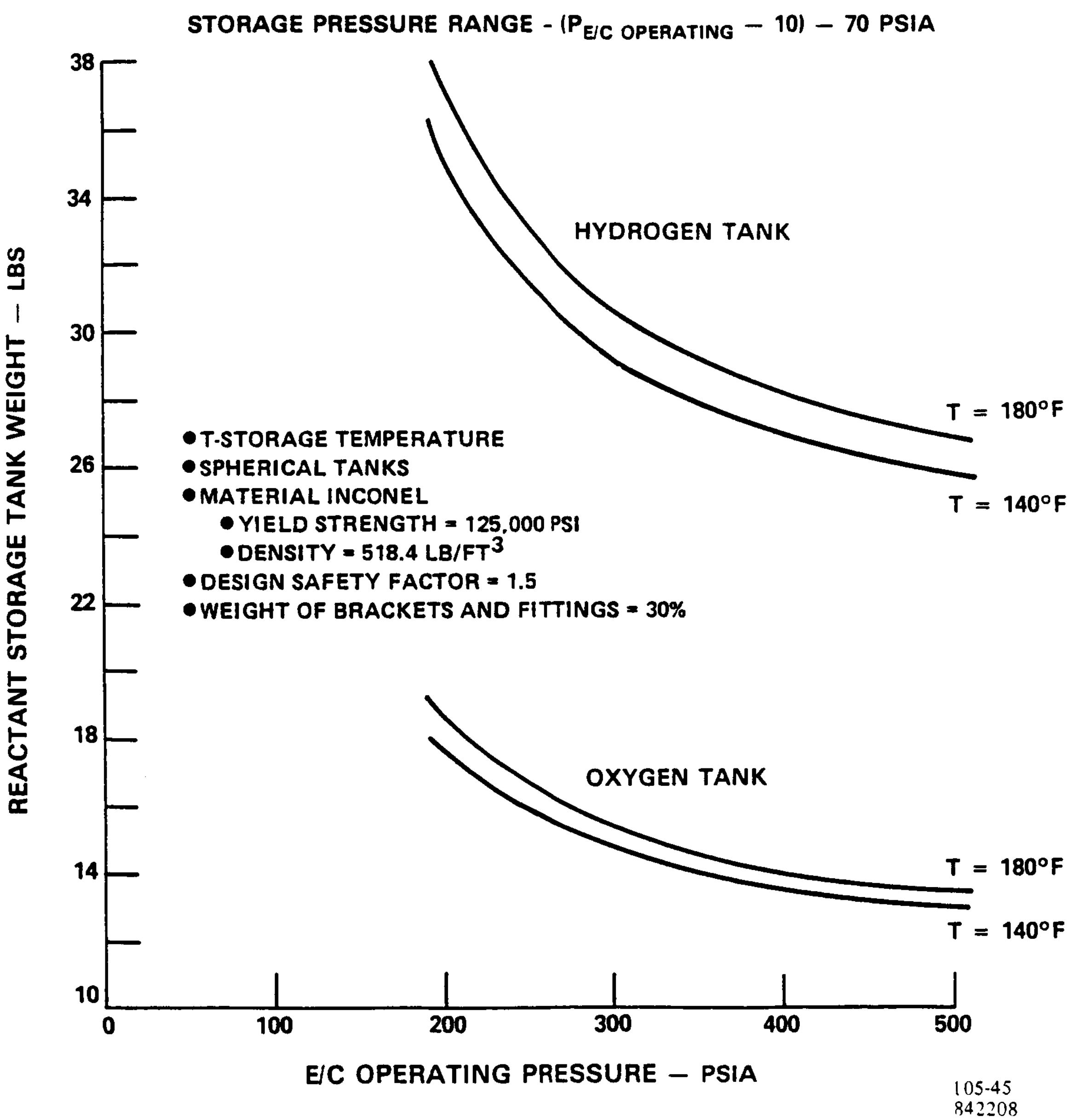

Figure 66. Reactant Storage Tank Weight

Table XVIII. H_2 and O_2 Storage Tank Thermal Parameters

- Maintain Tanks at System Operating Temperature During Both Charge and Discharge (Isothermal Compression and Expansion of Tank Contents)
- Environment
  - T_∞ = 20°R (11.1°K)
  - Radiation Only
- Insulation
  - Tank Cover Material - Gold Metalized Kapton Film Layers Separated By Microfiber Matt of Borosilicate
    - K = 0.00044 Btu/Ft-Hr-°F (In Space Vacuum) 0.0006549 cal/m-hr-°C
    - E - 0.15
    - Thickness = 2.0 in. (.0508 meters)
  - Connector and Mounting Bracket Thermal Dam Material - Molded (Rigid) Fiberglass
    - Heat Loss through Fittings and Mounting Brackets is Negligible

The storage tank thermal requirements are shown graphically in Figures 67 and 68. Both curves display the maximum magnitude of the heating required which occurs at the end of the charge cycle and the beginning of the discharge cycle. The variation in required heat input with time is small within each cyclic phase.

For the pressure regulators, heat losses to the environment were assumed to be insignificant. The heat inputs shown in Figure 69 are the maximum expected and occur when the pressure drop across each regulator is at maximum: at the beginning of the charge cycle for the electrolysis cell pressure regulator and at the beginning of the discharge cycle for fuel cell pressure regulators. As the cyclic phases proceed, the heat input requirements diminish.

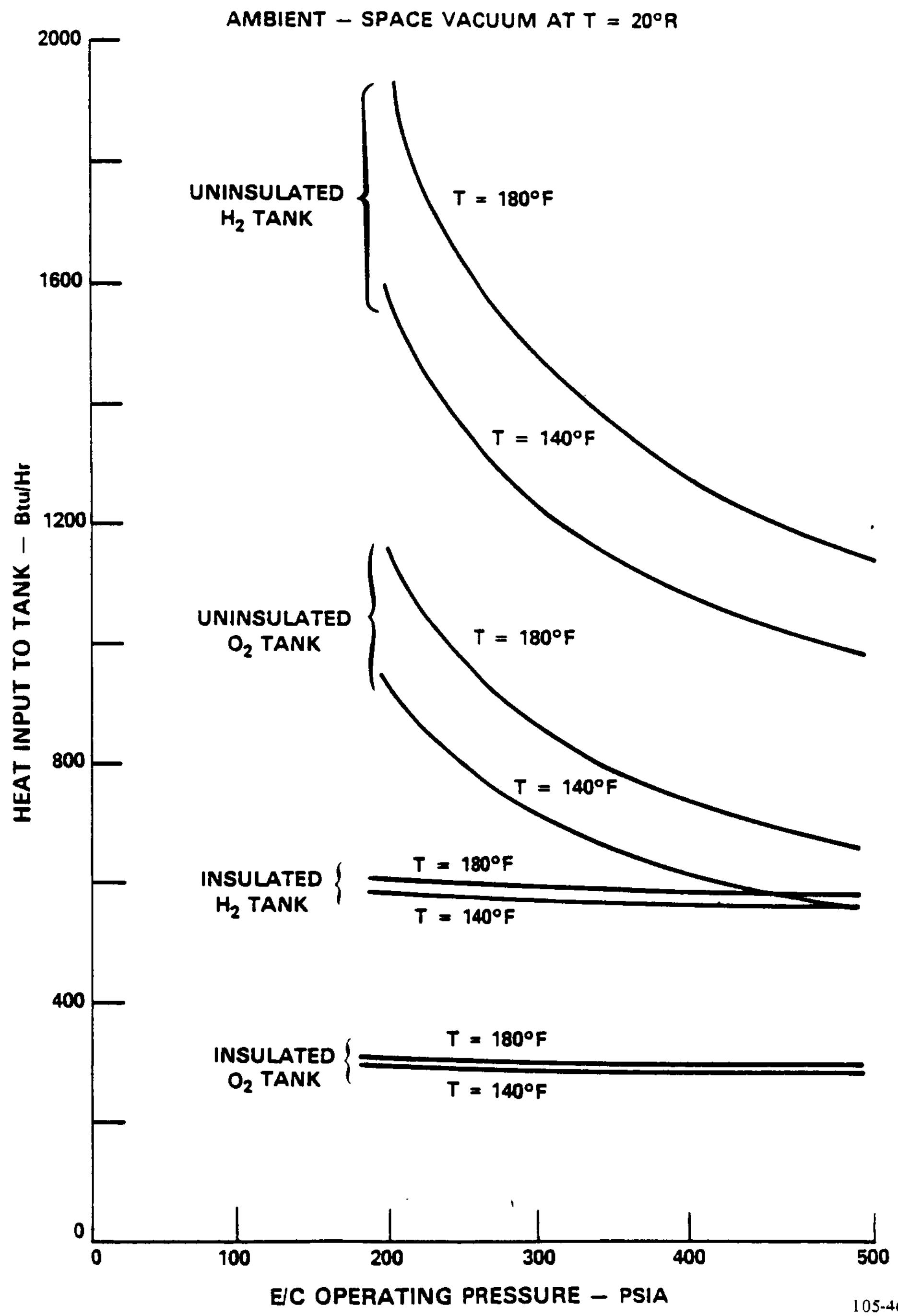

Figure 67. Heat Input to Maintain Reactant Storage Tanks at Constant Temperature During Discharge

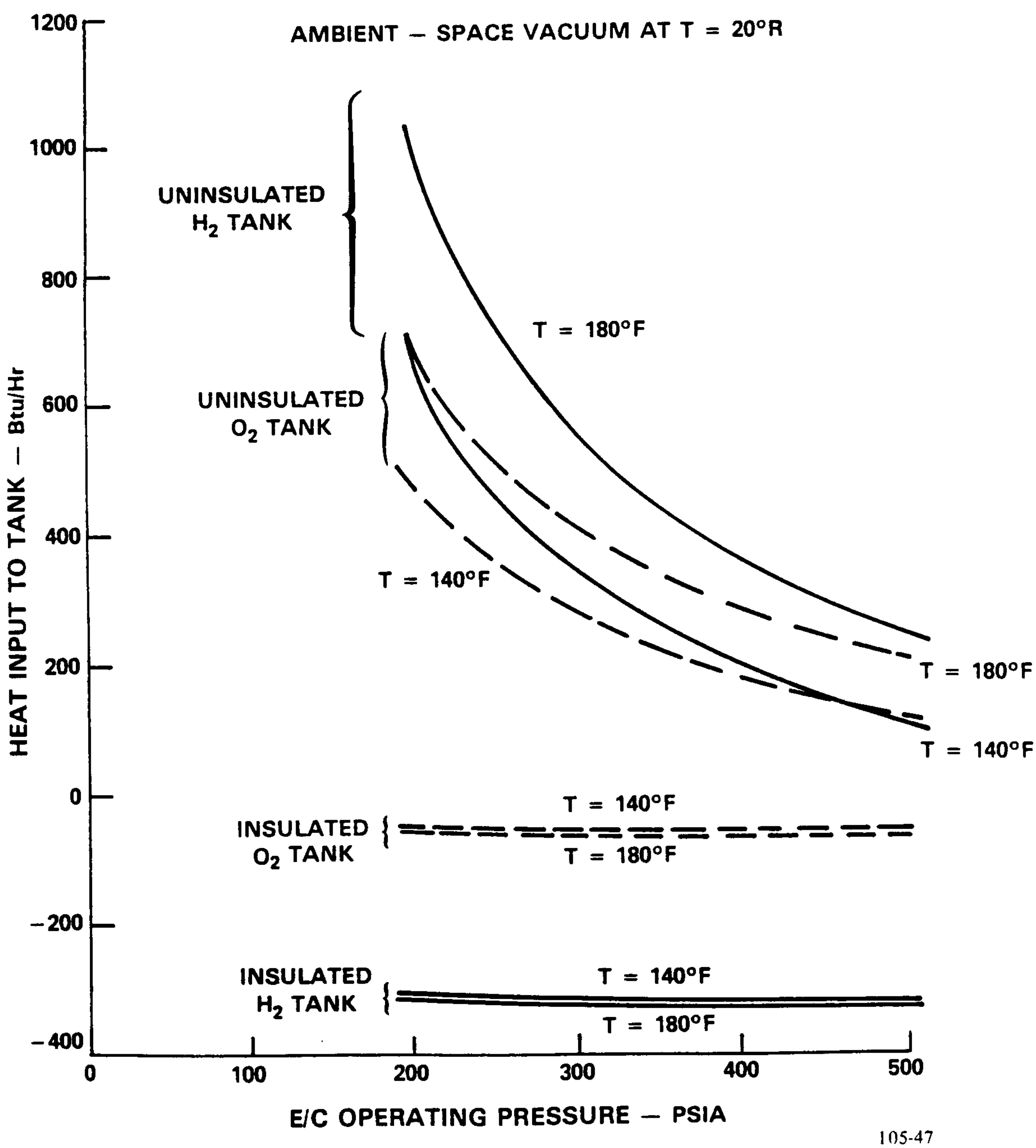

Figure 68. Heat Input to Maintain Reactant Storage Tanks at Constant Temperature During Charge

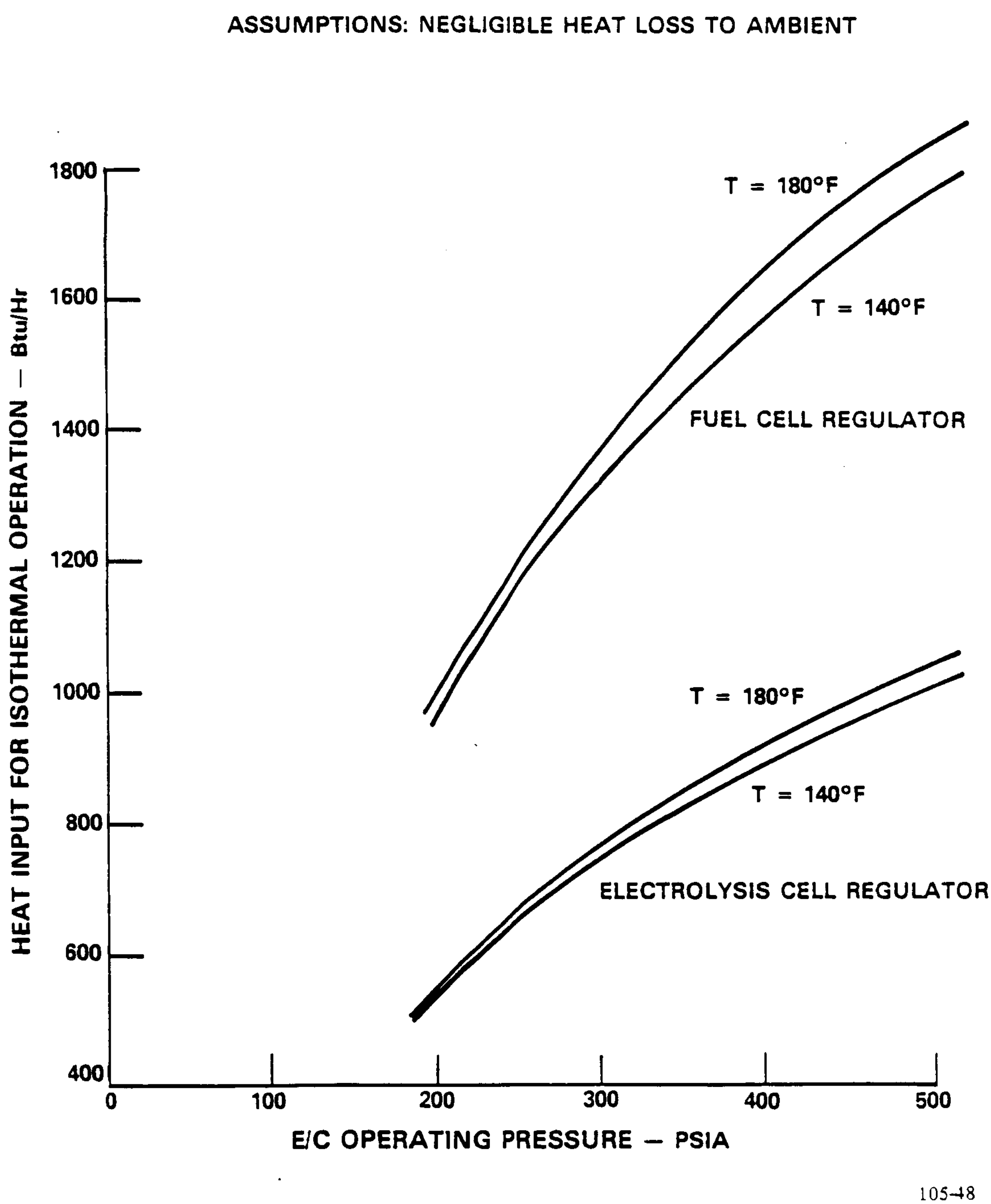

Figure 69. Maximum Heat Input to Pressure Regulators for Isothermal Operation

APPENDIX B

ENGINEERING MODEL SYSTEM COMPONENT REQUIREMENTS

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TABLE XIX. VALVE CHART

Component No.	CHV-1	CHV-2	PCV-1	PCV-2	PCV-3	PCV-4	TCV-1	TCV-2	TCV-3
Application	Product Water Check Valve	Feedwater Check Valve	F/C H2 Pressure Regulator	F/C O2 Pressure Regulator	E/C H2 Pressure Regulator	E/C O2 Pressure Regulator	F/C Stack Coolant Inlet Temp.	F/C Stack Coolant Exit Temp.	F/C Cond. H2 Exit Temp.
Fluid/Mol. Wt.	H2O/18.016	H2O/18.016	H2/2.016	O2/32.0	H2/2.016	O2/32.0	FC-40/650	FC-40/650	FC-40/650
Design Flow (pph)									
Max./Min. Flow (pph)	10	10					TBD	TBD	TBD
Design Tempera- ture (°F)									
Max./Min. Temp. (°F)							TBD	TBD	TBD
Design Pressure (psia)							60.0	60.0	60.0
Max./Min Pressure (psia)							TBD	TBD	TBD
P @ Design Flow (In. H2O)							TBD	TBD	TBD
Control Type	Check	Check	Regulator	Regulator	Regulator	Regulator	Mod.	Mod.	Mod.
Response Time (Sec.)	1	1	10	10	10	10	10	10	10
Shut-Off P (psid)	3	240	N/A	N/A	N/A	N/A			
Normal Position	Closed	Closed	Open	Open	Open	Open	Open to Main Flow	Open	Open
Comments									

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TABLE XX. INSTRUMENT CHART

Component No.	Application	Measurement Range	Alarm Limit	Shutdown Limit	Comments
TE-6	Condenser H2 Exit Temp.	40-180°F	TBD	TBD	Signal to TCV-3. Used in calculation of F/C KOH concentration.
TE-13	Coolant Return Temp.	40-120°F			For diagnostic use.
TE-16	F/C Stack Coolant Inlet Temp.	40-200°F	190°F 170°F		Signal to TCV-1 and/or HTR-1. Used in calculation of F/C KOH concentration.
TE-17	F/C Stack Coolant Exit Temp.	40-275°F	210°F	250°F	Signal to TCV-2. Used in calculation of F/C KOH concentration.
TE-18	F/C Reactant Regulator Coolant Exit Temp.	40-275°F	-	-	For diagnostic use.
TE-21	F/C Stack Coolant Inlet Temp.	40-225°F			For diagnostic use.
TE-22	F/C Stack Coolant Exit Temp.	40-275°F	210°F	250°F	Signal to HTR-2.
TE-23	H2 Tank Temperature	40-200°F			Tank temperatures used with tank.
TE-24	O2 Tank Temperature	40-200°F			Pressures to determine state-of-charge
PT-23	H2 Tank Pressure	0-400 psia	70 psia 300 psia		Tank pressures indicate state-of-charge. F/C unit shutdown when either pressure exceeds 300 psia regardless of solar exposure. Alarm if P between tanks 10 psi.
PT-24	O2 Tank Pressure	0-400 psia	70 psia 300 psia		
ET-1	F/C Terminal Voltage	0-150 V	100 V 130 V	90 V 140 V	
IT-1	F/C Terminal Current	0-150 Amps		TBD	
ET-2	F/C Terminal Voltage	0-			
IT-2	F/C Terminal Current	0-		TBD	
LV-4	Water Feed Tank Level	10-90% Full	8% Full	5% Full	

TABLE XXI. CONTROL STATUS CHART

Component No.	Start-Up		Stand-By		Run		Shutdown
	Charge	Discharge	Charge	Discharge	Charge	Discharge	Charge/Discharge
FCS-1	Off	On	Off	On**	Off	On	Off
ECS-1	On	Off	Off***	Off	On	Off	Off
PMP-1	On	On	On	On	On	On	Off
PMP-2	On	On	On	On	On	On	On
PMP-3	On*	On*	On*	On*	On*	On*	Off
HTR-1	On	On	Controlled	Controlled	Controlled	Controlled	Controlled
HTR-2	On	On	Controlled	Controlled	Controlled	Controlled	Controlled
TCV-1	Min. By-Pass	Max. By-Pass	Controlled	Controlled	Controlled	Controlled	Min. By-Pass
TCV-2	Full Open	Full Open	Full Open	Full Open	Full Open	Controlled	Full Open
TCV-3	Full By-Pass	Full By-Pass	Controlled	Controlled	Controlled	Controlled	Full By-Pass
FCV-1	Open to ECS-1	Open to FCS-1	Open to ECS-1	Open to FCS-1	Open to ECS-1	Open to FCS-1	Open to FCS-1
FCV-2	Open to ECS-1	Open to FCS-1	Open to ECS-1	Open to FCS-1	Open to ECS-1	Open to FCS-1	Open to FCS-1
PCV-1							
PCV-2			All pressure control valves are fully active in all modes				
PCV-3							
PCV-4							

* Intermittent
** Parasite power load only
*** On if reactant tank pressure drops below 100 psia

TABLE XXII. CONTROL SCHEDULES

Control Function	Controlled Component	Sensor	Schedule	Comments
FCS-1 Coolant Inlet Temperature	TCV-1	TE-16	180°F ± 5	Functions in stand-by and run mode.
FCS-1 Coolant Exit Temperature	TCV-2 HTR-1	TE-17 TE-17	205°F ± 5 180°F ± 5	Functions in stand-by mode and discharge phase of run mode.
FCS-1 H2 Condenser Exit Temperature	TCV-3	TE-6	150°F ± 2	Functions in stand-by and run mode.
ECS-1 Coolant Exit Temperature	HTR-2	TE-22	180°F ± 5	
FCS-1 H2 Pressure	PCV-1	-	60 psia ± 5	
FCS-1 O2 Pressure	PCV-2	-	60 psia ± 5	
FCS-1 H2/O2 Cross-Pressure	PCV-1 PCV-2	-		Cross-pressure given for H2 over O2.
ECS-1 H2 Pressure	PCV-3	-	300 psia + 10 - 0	
ECS-1 O2 Pressure	PCV-4	-	300 psia + 10 - 0	
ECS-1 H2/O2 Cross-Pressure	PCV-3 PCV-4	-	TBD	
ECS-1 H2O Feed Tank Flow	PMP-3	LV-4	0-100% Full	
Charge/Discharge Phase Selection	ECS-1 FCS-1	EE-2 PT-23 TE-23 PT-24 TE-24	TBD TBD	

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REFERENCES

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1. Martin, R. E., "Alkaline Fuel Cells for the Regenerative Fuel Cell Energy Storage System." 839250, 18th Intersociety Energy Conversion Engineering Conference, Orlando, Florida, August 1983

2. Martin, R. E., Sheibley, D. W., and Gitlow, B., "Alkaline Regenerative Fuel Cell Energy Storage System for Manned Orbital Satellites," 829361, 17th Intersociety Energy Conversion Engineering Conference, Los Angeles, CA, August 1982.

3. Martin, R. E., "Electrochemical Energy Storage for an Orbiting Space Station - Topical Report," United Technologies Corporation, Power Systems Division, FCR-3142, NASA CR-165436, December 1981.

4. Martin, R. E., "Advanced Technology Lightweight Fuel Cell Program - Final Report," United Technologies Corporation, Power Systems Division, FCR-3045, NASA CR-165417, August 1981.

5. Martin, R. E., Reid, M. A., and Schubert, F. N., "Alkaline Regenerative Fuel Cell Systems for Energy Storage," 819041, 16th Intersociety Energy Conversion Engineering Conference, Atlanta, GA, August 1981.

6. Martin, R. E., "Advanced Technology Lightweight Fuel Cell Program - Final Report," United Technologies Corporation, Power Systems Division, FCR-1657, NASA CR-159807, March 1980.

7. Martin, R. E., "Advanced Technology Lightweight Fuel Cell Power Plant Components Program - Final Report," United Technologies Corporation, Power Systems Division, FCR-1656, February 1980.

8. Martin, R. E., "Advanced Technology Lightweight Fuel Cell Program - Final Report," United Technologies Corporation, Power Systems Division, FCR-1017, NASA CR-159653, September 1979.

9. Martin, R. E., Gitlow, B., and Bell, W. F., "Strip Cell Test and Evaluation Program - Final Report," United Technologies Corporation, Power Systems Division, FCR-0945, NASA CR-159652, September 1979.

10. Martin, R. E., Gitlow, B., Meyer, A. P., and Bell, W. F., "Development of Advanced Fuel Cell System - Final Report," United Technologies Corporation, Power Systems Division, FCR-0398, NASA CR-159443, June 1976.

11. Meyer, A. P., and Bell, W. F., "Development of Advanced Fuel Cell System (Phase IV) - Final Report," United Technologies Corporation, Power Systems Division, FCR-0165, NASA CR-135030, January 1976.

12. Handley, L. M., Meyer, A. P., and Bell, W. F., "Development of Advanced Fuel Cell System (Phase III) - Final Report," United Aircraft Corporation, Pratt & Whitney Aircraft Division, PWA-5201, NASA CR-134818, January 1975.

13. Handley, L. M., Meyer, A. P., and Bell, W. F., "Development of Advanced Fuel Cell System (Phase II) - Final Report," United Aircraft Corporation, Pratt & Whitney Aircraft Division, PWA-4984, NASA CR-134721.

14. Grevstad, P. E., "Development of Advanced Fuel Cell System - Final Report," United Aircraft Corporation, Pratt & Whitney Aircraft Division, PWA-4542, NASA CR-121136.

15. Schubert, F. H., "Alkaline Electrolysis Information", Letter Report, FHS-1-20, Life Systems Inc., 24 January 1984.

16. Nutall, L. J., "Description and Parametric Data of SPE® Electrolysis Cells," ECOES-118, General Electric, March 1984.

17. Handbook of Failure Rates (Long Life Space Vehicle Investigations), Report =T-70-48891-007, Martin Marietta Corp., June 20, 1970.

18. Non-Electric Parts Reliability Data, NRPD-2, Reliability Analysis Center, Rome Air Development Center, Summer 1981.

19. Fuel Cell Technology Program - Final Reliability Summary and Analysis Report, NAS9-11034, PWA-4359, Pratt & Whitney Aircraft, December 15, 1971.

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16. Abstract

A study was conducted to define the characteristics of a Regenerative Fuel Cell System (RFCS) for low earth orbit Space Station missions. The study defined and characterized RFCS's based on both an alkaline electrolyte fuel cell integrated with an alkaline electrolyte water electrolyzer and an alkaline electrolyte fuel cell integrated with an acid solid polymer electrolyte (SPE) water electrolyzer. The study defined the operating characteristics of the systems including system weight, volume, and efficiency. A maintenance philosophy was defined and the implications of system reliability requirements and modularization were determined. Finally, an Engineering Model System was defined and a program to develop and demonstrate the EMS and pacing technology items that should be developed in parallel with the EMS were identified.

The specific weight of an optimized RFCS operating at 140°F (60°C) was defined as a function of system efficiency for a range of module sizes. For a 33.3 kW module operating at 50% efficiency, the specific weight was 19.8 watt-hr/lb (43.6 watt-hr/kg). An advanced technology system operating at 180°F (82.2°C) yielded 23.2 watt-hrs/lb (watt-hrs/kg). For a higher efficiency design point, i.e., 55%, the specific weight decreases by approximately 15%.

An Engineering Model System operating at a nominal temperature 180°F (82.2°C) and capable of delivery 10 kW at an overall efficiency of 55.4% is described. A program to develop the EMS is described including a technology development effort for pacing technology items. The pacing technology items include fuel cell stack components, electrolyzer stack components and selected ancillary components.

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